Exhibit JJ

Exhibit E-11

Invalidity of U.S. Patent No. 7,725,253 ("'253 Patent")[1] under Pre-AIA Section 102 or Section 103 in view of the HiBall Tracking System ("HiBall")[2]

HiBall was publicly available at least as of 1999. Plaintiffs belatedly asserted a priority date of June 13, 2001 for the '253 Patent on December 22, 2021, 71 days after the Court's deadline. Defendants have reviewed Plaintiffs' alleged evidence of the purported June 13, 2001 priority date, and maintain that the '253 Patent is not entitled to this priority date. *See* Defendants' March 15, 2022 Supplemental Invalidity Contentions. Defendants reserve their objections to Plaintiffs' belated assertion of the new priority date and expressly reserve all rights to challenge this alleged new priority date. As such, Defendants assume for the sake of these invalidity contentions, that the priority date for the '253 Patent is August 9, 2002 based on the first filed Provisional Application from which the '253 Patent claims priority. (Defendants do not concede nor agree that Plaintiffs are even entitled to this date.) Assuming this priority date, HiBall qualifies as prior art under at least pre-AIA Sections 102(a) and (b) to the '253 Patent.

As described herein, the asserted claims of the '253 Patent are invalid (a) under one or more sections of 35 U.S.C. § 102 as anticipated expressly or inherently by HiBall (including the documents incorporated into HiBall by reference) and (b) under 35 U.S.C. § 103 as obvious in view of HiBall standing alone and, additionally, in combination with the knowledge of one of ordinary skill in the art, and/or other prior art, including but not limited to the prior art identified in Defendants' Invalidity Contentions and the prior art described in the claim charts attached in Exhibits E-1 – E-23. With respect to the proposed modifications to HiBall, as of the priority date of the '253 Patent, such modification would have been obvious to try, an obvious combination of prior art elements according to known methods to yield predictable results, a simple substitution of one known element for another to obtain predictable results, a use of known techniques to improve a similar device or method in the same way, an application of a known technique to a known device or method ready for improvement to yield predictable results, a variation of a known work in one field of endeavor for use in either the same field or a different one based on design incentives or other market

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1 Discovery in this case is ongoing and, accordingly, this invalidity chart is not to be considered final. Defendants have conducted the invalidity analysis herein without having fully undergone claim construction and a *Markman* hearing. By charting the prior art against the claim(s) herein, Defendants are not admitting nor agreeing to Plaintiffs' interpretation of the claims at issue in this case. Additionally, these charts provide representative examples of portions of the charted references that disclose the indicated limitations under Plaintiffs' application of the claims; additional portions of these references other than the representative examples provided herein may also disclose the indicated limitation(s) and Defendants contend that the asserted claim(s) are invalid in light of the charted reference(s) as a whole. Defendants reserve the right to rely on additional citations or sources of evidence that also may be applicable, or that may become applicable in light of claim construction, changes in Plaintiffs' infringement contentions, and/or information obtained during discovery as the case progresses. Further, by submitting these invalidity contentions, Defendants do not waive and hereby expressly reserve their right to raise other invalidity defenses, including but not limited to defenses under Sections 101 and 112. Defendants reserve the right to amend or supplement this claim chart at a later date, including after the Court's order construing disputed claim terms.

2 The claim limitations described herein were disclosed by HiBall as of the earliest priority date of the '253 patent. For instance: G. Welch, *et al.,* High-Performance Wide-Area Optical Tracking The HiBall Tracking System, Presence: Teleoperators and Virtual Environments (10:1), February 2001 ("Welch HiBall"); UNC HiBall Tracker, https://www.cs.unc.edu/~tracker/media/html/hiball.html, July 10, 2000 ("UNC HiBall Tracker"); 3rdTech, *HiBall-3000 Wide-Area Tracker and 3D Digitizer*, 2001 ("3rdTech"); Computer Graphics World, *On the Right Track*, April 2000 ("On the Right Track"); G. Welch, *et al.,*The HiBall Tracker: *High-Performance Wide-Area Tracking for Virtual and Augmented Environments*, 1999 (Welch 1999).

forces with variations that are predictable to one of ordinary skill in the art, and/or obvious in view of teachings, suggestions, and motivations in the prior art that would have led one of ordinary skill to modify or combine the prior art references.

All cross-references should be understood to include material that is cross-referenced within the cross-reference. Where a particular figure is cited, the citation should be understood to encompass the caption and description of the figure as well as any text relating to or describing the figure. Conversely, where particular text referring to a figure is cited, the citation should be understood to include the figure as well.

A. Independent Claim 1

Claim 1	HiBall
[1.pre] A tracking system comprising:	At least under Plaintiffs' apparent infringement theory, HiBall discloses, either expressly or inherently, a method for tracking an object. No party has yet asserted that the preamble is limiting, nor has the Court construed the preamble as limiting. However, to the extent that the preamble is limiting, it is disclosed by HiBall. In the alternative, this element would be obvious over HiBall in light of the other references disclosed in Defendants' Invalidity Contentions and/or the knowledge of one of ordinary skill in the art. *See, e.g.*:

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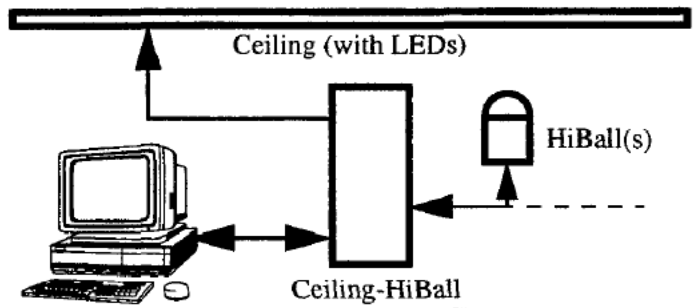
CLAIM 1	HiBall
	3. SYSTEM OVERVIEW  **Figure 2. A block diagram of the HiBall tracking system.** Welch 1999 at Fig. 2. The HiBall tracker system (Figure 2) provides six-degree-of freedom ***tracking of devices*** in real time. An outward looking infrared-sensing subsystem called a HiBall (Figure 1, lower-right) is mechanically fixed to each device to be tracked. The HiBalls view an environment containing a subsystem of fixed-location infrared beacons which we call the Ceiling. At the present time, the beacons are in fact entirely located in the ceiling of our laboratory, but could as well be located in walls or other arbitrary fixed locations. These subsystems are coordinated by a Ceiling-HiBall Interface Board (CIB) which provides communication and synchronization functions between the host computer and the attached subsystems. Each HiBall has 26 narrow (less than 6 degree) views distributed over a large solid angle. Beacons are selectively flashed in a sequence such that they are seen by many different fields of view of each HiBall. Initial acquisition is performed using a brute force search through beacon space, but once initial lock is made, the selection of beacons to flash is tailored to the fields of view of the HiBalls. Tracking is maintained using a Kalman filter-based prediction-correction algorithm known as SCAAT. This technique has been further extended to provide self-calibration of the Ceiling on-line with the tracking of the attached HiBalls. Welch 1999 at 2.

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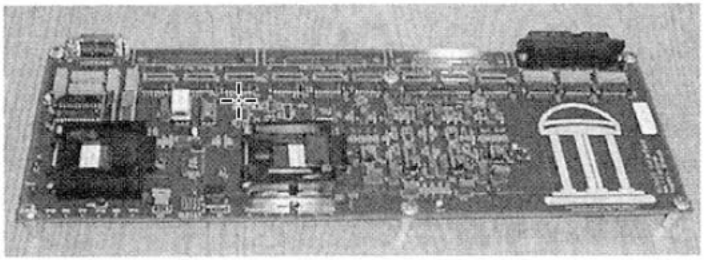
CLAIM 1	HiBall
	4.3 The Ceiling-HiBall Interface Board The Ceiling-HiBall Interface Board (CIB), shown below in Figure 4, provides communication and synchronization between a host personal computer, the Ceiling (section 4.1) and the HiBall (section 4.2).  **Figure 4. The Ceiling-HiBall Interface Board (CIB). The CIB shown is 19 inches, the newest revision is 14 inches.** Welch 1999 at 3. As part of an ongoing effort to develop a system that avoids such tradeoffs, the Tracker Research Group at the University of North Carolina (http:/ /www.cs.unc.edu/-tracker) has created a wide-area optoelectronic tracking technology that lets users move freely through full-scale virtual worlds in real time. Such a capability not only enables VR applications that would otherwise be difficult or impossible to achieve-such as the exploration of life-size architectural designs and room-filling molecular models-but it is also expected to be of value to augmented reality (AR). In AR, real and digital worlds are superimposed into one scene through the use of see-through head-mounted displays that rely either on mirrors to represent the physical world or video input. Highly accurate motion tracking is crucial because even small tracking errors can result in unacceptable misregistration between real and virtual objects. Called the HiBall Tracking System, the new technology is able to meet the needs of such applications through its implementation of four unique components: ceiling panels that house LED targets, a miniature optical-sensor cluster (the HiBall) that senses and digitizes the LED flashes, a custom interface board that facilitates communications among the various components of the system, and tracking software that processes the communications in real time.

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CLAIM 1	HiBall
	On the Right Track at 2. **Inside-Out Tracking** Unlike traditional optical tracking methods, in which targets are attached to the object or person to be tracked and sensed by a camera in the environment, the HiBall system employs an "inside-out" approach, in which the sensors are user mounted and the LED targets are fixed in the environment. This distinction is important, says UNC research assistant professor Greg Welch, because it ensures constant sensitivity to orientation over the working area. Also, because the targets are in the ceiling tiles, the tracking environment is infinitely scalable by increasing the number of tiles. The HiBall itself is unique in that it does not rely on the same charged-couple devices (CCDs) that most digital cameras employ. Rather, it uses lateral-effect photo diodes (LEPDs). Unlike CCD's, LEPDs are not imaging devices. They are 2D optical sensors that produce four analog voltages, which together indicate the 2D position of the center of the light hitting the sensor. "There is no image to capture and interpret, simply four voltages to digitize, which is done right inside the HiBall;' says Welch. The control center of the tracking system is the Ceiling-HiBall Interface Board (CIB), which sends LED addresses and control signals to the ceiling to direct the flashing of the LEDs. It also communicates with the HiBall, sending control signals and receiving the digitized LEPD values. The PC tracking software sends requests to the CIB for a sample of a particular ceiling LED from a particular optical sensor. In response, the CIB tells the ceiling to flash the LED and tells the HiBall to sample the LEPD. The digitized LEPD data it receives is sent back to the PC. The system's tracking code relies on an estimation approach called SCAAT (single constraint at a time) tracking, which turns the individual LED sightings into a complete position and orientation, or pose, estimate for the HiBall. With SCAAT, individual observations are reported as soon as they're acquired, rather than at the end of a complete collection of measurements, providing some information about the user's pose. Subsequent measurements build on previous ones to improve the estimates. A filtering technique fuses a continuous sequence of these incomplete, single LED sightings into an ongoing sequence of complete estimates. To enhance the quality of the estimates and ensure low latency, thousands of LED sightings are generated per second. An autocalibration process compensates for shifts in the tiles and for inherent estimate inaccuracies. On the agenda for the HiBall system is the development of a wireless capability between the HiBall and the CIB. The researchers are also investigating more flexible LED strategies, including LED strips that can be hung from ceilings wherever needed. The group's long-term objective is to develop hybrid tracking approaches that will reduce the system's infrastructure to allow users to move beyond the lab, eventually outdoors, while maintaining system performance. In the meantime, the existing HiBall technology is headed toward commercialization by a new company called HiBall Tracker Inc., which is currently negotiating a technology license with UNC Chapel Hill.

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CLAIM 1	HiBall
	On the Right Track at 2. **New Tracking Technology** The HiBall-3000 Tracker is a new approach to wide-area tracking, delivering unmatched accuracy with low latency, high update rate, and scalability to cover a very large region. Based on results of the Wide-Area Tracking research project of the Department of Computer Science of the University of North Carolina at Chapel Hill — the HiBall-3000 optical tracker achieves new levels of performance for virtual and augmented reality, simulation and training, film and video production, and entertainment. The HiBall-3000 has a unique set of features. The HiBall-3000 tracker: Scales to cover very large areas, almost without limit Maintains extraordinary precision throughout the tracking space Delivers precision unaffected by metal, magnetic fields, or noise, and built-in redundancy overcomes most line-of-sight obstructions Provides very high update rate and low latency — solid, smooth tracking even with high-speed motion. The HiBall-3000's optical tracker has been designed for the most demanding applications, achieving new levels of range, accuracy, and update rate. 3rdTech at 1. **The HiBall-3000 Optical Sensor** The HiBall-3000 tracker system is composed of two key integrated components; the HiBall Optical Sensor and the HiBall Ceiling Beacon Arrays. The HiBall Optical Sensor is composed of 6 lenses and photodiodes arranged so that each photodiode can 'view' infrared LEDs, in the Beacon Arrays mounted on the ceiling, through several of the 6 lenses. The assembly includes signal processing and analog-to-digital conversion circuitry. The total weight is about 6 ounces, making it light enough to comfortably mount on a headmounted display or hand-held device. By locating the sensors on the person or object being tracked — *inside-out tracking* — sensitivity around the working area is increased and the tracker area scales almost without limit. An entire lab, movie set, or assembly area can be tracked. The HiBall can also be mounted on a small probe or stylus, enabling extremely accurate measurements of individual objects within a large space. For example, this can be used for very rapid measurement of actual television or movie sets or other real-world objects to be combined with virtual scenes. No other device can provide comparable speed and accuracy over a wide area. 3rdTech at 1.

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CLAIM 1	HiBall
	HiBall Beacon Array Modules The infrared LEDs 'seen' by the HiBall Sensor are embedded in a series of ceiling mounted strips forming a 2D Beacon Array - 8 LEDs per strip; 6 strips per Beacon Array Module (BAM). These strips are designed to slip easily into a typical 'drop ceiling' with no changes required in panels, lights, vents, etc. - the more BAMs employed, the greater the range of the tracker. The arrays are highly modular — available in configurations covering as little as 64 square feet (8' x 8') or more than 1,600 square feet (40' x 40'). And no special adjustments are required to the ceiling structure — the system's precision is unaffected by typical variations in ceiling height. The HiBall Sensor and the Beacon Arrays are synchronized by a Ceiling- HiBall Interface Board (CIB), part of the system's integrated PC, which enables extremely high rates of LED 'sightings'— approximately 2,000 per second. This results in a tracker update rate of 2,000 Hz — several times faster than other commercially available wide-area trackers. Faster updates means lower latency and more accurate tracking - even with rapid movements. **AutoCalibration** The system makes use of a *single constraint at a time* (SCAAT) algorithm to compute the location and orientation of the HiBall Sensor at every LED sighting. In addition, the system incorporates *auto-calibration* — tuning the modeled location of individual LEDs on every update. This accommodates typical shifts and movements in the ceiling tiles and BAMs without loss of accuracy or performance. **Applications** The range and performance of the HiBall-3000 Tracker open up new possibilities for large-scale virtual reality such as exploring full-size architectural designs or engineering prototypes. Its precision enables largescale augmented reality for applications in medicine, training and entertainment where accurate correspondence between physical reality and the virtual world are critical. **Proven Results** Developed in the Computer Science Department of the University of North Carolina at Chapel Hill (see www.cs.unc.edu/~tracker), the original HiBall tracker has been in use since 1997 and has consistently exceeded performance expectations. 3rdTech at 1.

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CLAIM 1	HiBall

HiBall-3000 Specifications and Performance

Hardware Components

HiBall Optical Sensor(s)	2 7/8" tall, 2 1/8" diam, 6 OZ
Beacon Array Module (BAM)	Six 2' x 1" x 7/8" strips, 8 sq. ft.
PC-based Controller	Includes CIB I/F Board
Connections	Ethernet (VRPN), Serial (Standard Library Interface)

Software Components

VR Peripheral Network (VRPN) support	Integrate system with other VR devices
Standard Library Interface	Compatible with existing systems
HBT Toolkit	Tools for set up, configuration and testing
HBT Library	Low-level system access
Output	Stream or point mode; XYZ coordinates; Quaternion, Euler angles or rotation matrices

3rdTech at 2.

HiBall-3000 Wide-Area Tracker Features

• Very Wide Area	Scalable to over 1,600 sq.ft.
• High Precision	Ideal for augmented reality apps and rapid scene digitizing
• High-update, low latency	Solid, high-speed tracking; no "swimming"
• Small, light sensor	Head or stylus mountable
• Easy installation	Installs in standard drop-ceilings; requires no room modifications
• Multiple sensors	Multiple participants or head plus hand tracking
• No metal/sound interference	Requires no modification of the environment
• Accurate every-where	Consistent tracking near edges of space as well as in center

3rdTech at 2.

3. SYSTEM OVERVIEW

The HiBall Tracking System consists of three main components (Figure 6). An outward-looking sensing unit we call the *HiBall* is fixed to each user to be tracked. The HiBall unit observes a subsystem of fixed-location infrared LEDs we call the *Ceiling* 1. Communication and synchronization between the host computer and these subsystems is coordinated by the *Ceiling-HiBall Interface Board* (CIB). In Section 4 we describe these components in more detail. Each HiBall observes LEDs through multiple sensor-lens *views* that are distributed over a large solid angle. LEDs are sequentially flashed (one at a time) such that they are seen via a diverse set of views for each HiBall.

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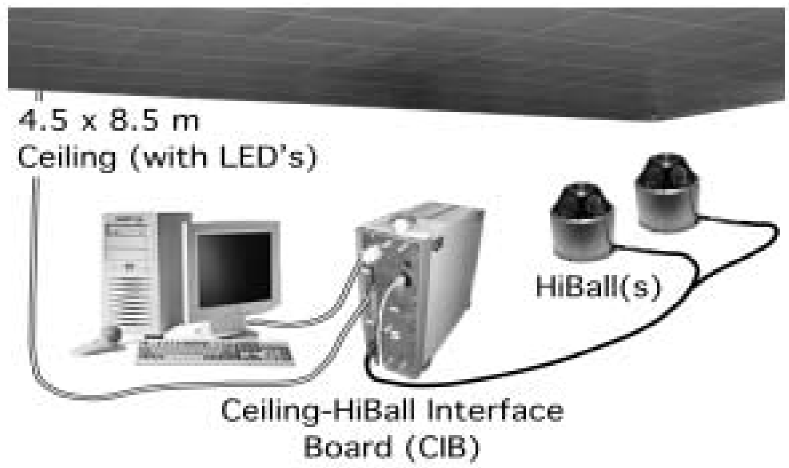
CLAIM 1	HiBall
	Initial *acquisition* is performed using a brute force search through LED space, but once initial lock is made, the selection of LEDs to flash is tailored to the views of the active HiBall units. Pose estimates are maintained using a Kalman-filter-based prediction-correction approach known as *single-constraint-at-a-time* or SCAAT tracking. This technique has been extended to provide self-calibration of the Ceiling, concurrent with HiBall tracking. In Section 5 we describe the methods we employ, including the initial acquisition process and the SCAAT approach to pose estimation, with the *autocalibration* extension. Welch HiBall at 6.  **Figure 6** Welch HiBall at Fig. 6. **4.3 The Ceiling-HiBall Interface Board** The Ceiling-HiBall Interface Board or CIB (Figure 11) provides communication and synchronization between a host personal computer, the HiBall (Section 4.1), and the Ceiling (Section 4.2). The CIB has four Ceiling ports allowing interleaving of ceiling panels for up to four simultaneous LED flashes and/or higher Ceiling bandwidth. (The Ceiling bandwidth is inherently limited by LED power restrictions as described in Section 4.2, but this can be increased by spatially multiplexing the Ceiling panels.) The CIB has two tether interfaces that can

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CLAIM 1	HiBall
	communicate with up to four daisy-chained HiBall units. The full-duplex communication with the HiBall units uses a modulation scheme (BPSK) allowing future wireless operation. The interface from the CIB to the host PC is the stable IEEE1284C extended parallel port (EPP) standard. The CIB comprises analog drive and receive components as well as digital logic components. The digital components implement store and forward in both directions and synchronize the timing of the LED "on" interval within the HiBall dark-light-dark intervals (Section 5.2). The protocol supports full-duplex flow control. The data are arranged into packets that incorporate error detection. Welch HiBall at 8-9. **4. SYSTEM COMPONENTS** **4.1 The HiBall** The original electro-optical tracker (Figure 3, bottom) used independently housed lateral effect photo-diode units (LEPDs) attached to a light-weight tubular framework. As it turns out, the mechanical framework would flex (distort) during use, contributing to estimation errors. In part to address this problem the HiBall sensor unit was designed as a single rigid hollow ball having dodecahedral symmetry, with lenses in the upper six faces and LEPD on the insides of the opposing six lower faces (Figure 7). This immediately gives six primary "camera" *views* uniformly spaced by 57 degrees. The views efficiently share the same internal air space, and are rigid with respect to each other. In addition, light entering any lens sufficiently off axis can be seen by a neighboring LEPD, giving rise to five secondary views through the top or central lens, and three secondary views through the five other lenses. Overall, this provides 26 fields of view which are used to sense widely separated groups of LEDs in the environment. While the extra views complicate the initialization of the Kalman filter as described in Section 5.5, they turn out to be of great benefit during steady-state tracking by effectively increasing the overall HiBall field of view without sacrificing optical sensor resolution. The lenses are simple plano-convex fixed-focus lenses. Infrared (IR) filtering is provided by fabricating the lenses themselves from RG-780 Schott glass filter material which is opaque to better than 0.001% for all visible wavelengths, and transmissive to better than 99% for IR wavelengths longer than 830 nm. The longwave filtering limit is provided by the DLS-4 LEPD silicon photodetector (UDT Sensors, Inc.) with peak responsivity at 950 nm but essentially blind above 1150 nm. The LEPDs themselves are not imaging devices; rather they detect the centroid of the luminous flux incident on the detector. The x-position of the centroid determines the ratio of two output currents, while the y-position determines the ratio of two other output currents. The total output current of each pair are commensurate, and

CLAIM 1	HiBall
	proportional to the total incident flux. Consequently, focus is not an issue, so the simple fixed-focus lenses work well over a range of LED distances from about half a meter to infinity. The LEPDs and associated electronic components are mounted on a custom rigid-flex printed circuit board (Figure 8). This arrangement makes efficient use of the internal HiBall volume while maintaining isolation between analog and digital circuitry, and increasing reliability by alleviating the need for inter-component mechanical connectors. Figure 9 shows the physical arrangement of the folded electronics in the HiBall. Each LEPD has four transimpedance amplifiers (shown together as one “Amp” in Figure 9), the analog outputs of which are multiplexed with those of the other LEPDs, then sampled, held, and converted by four 16-bit Delta-Sigma analog-to-digital (A/D) converters. Multiple samples are integrated via an accumulator. The digitized LEPD data are organized into packets for communication back to the CIB. The packets also contain information to assist in error-detection. The communication protocol is simple, and while presently implemented by wire, the modulation scheme is amenable to a wireless implementation. The present wired implementation allows multiple HiBall units to be daisy-chained so a single cable can support a user with multiple HiBall units. Welch HiBall at 6-7. **1.3 The HiBall Tracking System** In this article we describe a new and vastly improved version of the 1991 system. We call the new system the *HiBall Tracking System*. Thanks to significant improvements in hardware and software this HiBall system offers unprecedented speed, resolution, accuracy, robustness, and flexibility. The bulky and heavy sensors and backpack of the previous system have been replaced by a small *HiBall* unit (Figure 4, bottom). In addition, the precisely machined LED ceiling panels of the previous system have been replaced by looser-tolerance panels that are relatively inexpensive to make and simple to install (Figure 4, top; Figure 10). Finally, we are using an unusual Kalman-filter-based algorithm that generates very accurate pose estimates at a high rate with low latency, and simultaneously self-calibrates the system. As a result of these improvements the HiBall Tracking System can generate over 2000 pose estimates per second, with less than one millisecond of latency, better than 0.5 millimeters and 0.03 degrees of absolute error and noise, everywhere in a 4.5 by 8.5 meter room (with over two meters of height variation). The area can be expanded by adding more panels, or by using checkerboard configurations which spread panels over a larger area. The weight of the user-worn HiBall is about 300 grams, making it lighter than one optical sensor in the 1991 system. Multiple HiBall units can be daisy chained together for head or hand tracking, pose-aware input devices, or precise 3D point.

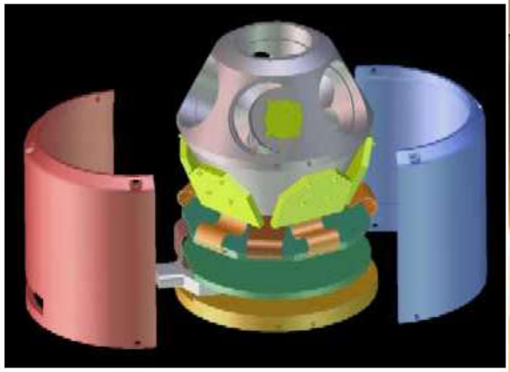
Exhibit E-11

<table>
<tr><th>CLAIM 1</th><th>HiBall</th></tr>
<tr><td></td><td>
Welch HiBall at 4.

The HiBall tracking system resolves linear motion of less than 0.2mm and angular motions under 0.03 degrees without the distortion seen in magnetic trackers. The update rate is greater than 1500 Hz and latency is about 1ms. To our knowledge, this was the first and remains the only demonstrated scalable tracking system for HMDs.
UNC HiBall Tracker at 1.

The HiBall
The HiBall is a cluster of 6 lenses and 6 photodiodes arranged so that each photodiodes can view LEDs through several of the 6 lenses, providing 26 view frustra originating at the HiBall. The assembly will include signal processing and A/D conversion circuitry. The total weight is about 5 ounces, making it lighter than just one of the cameras in the previous generation ceiling tracker.

The HiBall and the ceiling panel are synchronized by a custom interface board which allows very high rate of LED sightings. The hardware alone can perform more than 3,000 sightings per second, while the whole system tracks using about 1,500.
UNC HiBall Tracker at 1.

The Hiball
(Shown without lenses)


</td></tr>
</table>

CLAIM 1	HiBall
	UNC HiBall Tracker at 2. **The SCAAT algorithm** The UNC HiBall Tracker relies on the SCAAT (Single Constraint At A Time) algorithm to compute the user's position and orientation from the individual sightings the HiBall makes of LEDs on the ceiling panels. The algorithm makes innovative use of an Extended Kalman Filter to provide position and orientation updates after each individual LED sighting, rather than after a group of several sightings as in the previous generation of UNC ceiling tracker. In addition, SCAAT improves on previously developed auto calibration techniques to allow on-line calibration as described below. For more information see Greg Welch's SCAAT page which includes links to Greg Welch and Gary Bishop's 1997 SIGGRAPH paper on SCAAT. UNC HiBall Tracker at 2. **Autocalibration** The current ceiling's lower cost design was made possible by an auto calibration process described in Gottschalk93. The SCAAT algorithm improves on this by allowing auto calibration, tuning the actual LED positions, to be performed while the system is tracking. This accommodates shifts in the tiles and LEDs which can occur during normal use. In addition this technique opens possibilities for even less initial knowledge of LED placement than the current ceiling provides. As a test and demonstration of the autocalibration abilities of SCAAT, we have intentionally raised ceiling panels from their correct position. Here Dr. Gary Bishop is shown making the adjustments. The system was given only the initial flat LED positions, but after less than ten minutes of use (successfully tracking with the misplaced panels), SCAAT had accurately adjusted its knowledge of the LED positions through displacements more than 5cm. The above visualization shows the final measured LED positions. UNC HiBall Tracker at 2-3.

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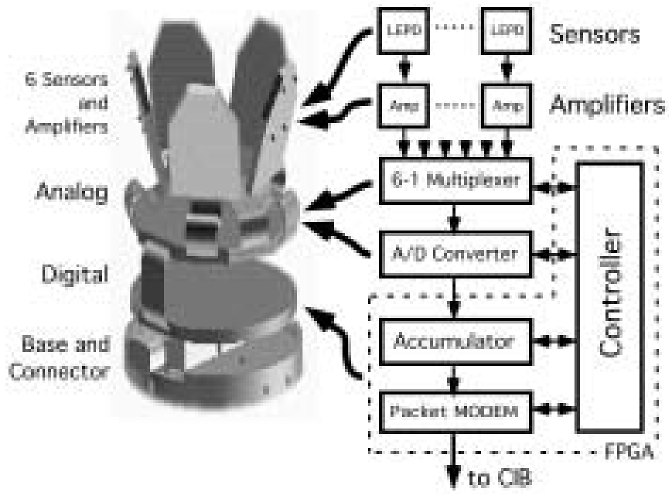
CLAIM 1	HiBall
	 **Figure 9** Welch HiBall at Fig. 9. **4.2 The Ceiling** As presently implemented, the infrared LEDs are packaged in 61 centimeter square *panels*, to fit a standard false ceiling grid (Figure 10, top). Each panel uses five printed circuit boards: a main controller board and four identical transverse-mounted *strips* (bottom). Each strip is populated with eight LEDs for a total of 32 LEDs per panel. We mount the assembly on top of a metal panel such that the LEDs protrude through 32 corresponding holes. The design results in a Ceiling with a rectangular LED pattern with periods of 7.6 and 15.2 centimeters. This spacing is used for the initial estimates of the LED positions in the lab, then during normal operation the SCAAT algorithm continually refines the LED position estimates (Section 5.4). The SCAAT *autocalibration* not only relaxes design and installation constraints, but provides greater precision in the face of initial and ongoing uncertainty in the Ceiling structure. We currently have enough panels to cover an area approximately 5.5 by 8.5 meters with a total of approximately 3,000 LEDs. 1 The panels are daisy-chained to each other, and panel selection encoding is position (rather than device) dependent. Operational commands are presented to the first panel of the daisy chain. At each panel, if the panel select code is zero the controller decodes and executes the operation; else it decrements the panel select code and passes it along to the next panel (controller). Upon decoding, a particular LED is selected and the LED is energized. The LED brightness (power) is selectable for *automatic gain control* as

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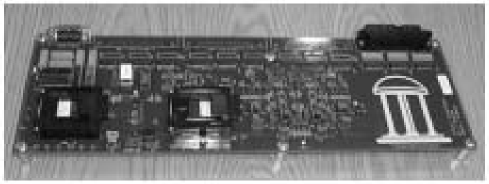
CLAIM 1	HiBall
	described in Section 5.2. We currently use Siemens SFH-487P GaAs LEDs which provide both a wide angle radiation pattern and high peak power, emitting at a center wavelength of 880 nm in the near IR. These devices can be pulsed up to 2.0 Amps for a maximum duration of 200 with a 1:50 (on:off) duty cycle. While the current Ceiling architecture allows flashing of only one LED at a time, LEDs may be flashed in any sequence. As such no single LED can be flashed too long or too frequently. We include both hardware and software protection to prevent this. **4.3 The Ceiling-HiBall Interface Board** The Ceiling-HiBall Interface Board or CIB (Figure 11) provides communication and synchronization between a host personal computer, the HiBall (Section 4.1), and the Ceiling (Section 4.2). The CIB has four Ceiling ports allowing interleaving of ceiling panels for up to four simultaneous LED flashes and/or higher Ceiling bandwidth. (The Ceiling bandwidth is inherently limited by LED power restrictions as described in Section 4.2, but this can be increased by spatially multiplexing the Ceiling panels.) The CIB has two tether interfaces that can communicate with up to four daisy-chained HiBall units. The full-duplex communication with the HiBall units uses a modulation scheme (BPSK) allowing future wireless operation. The interface from the CIB to the host PC is the stable IEEE1284C extended parallel port (EPP) standard. The CIB comprises analog drive and receive components as well as digital logic components. The digital components implement store and forward in both directions and synchronize the timing of the LED "on" interval within the HiBall dark-light-dark intervals (Section 5.2). The protocol supports full-duplex flow control. The data are arranged into packets that incorporate error detection. Welch HiBall at 8-9.  **Figure 11** Welch HiBall at Fig. 11. *See also* /hiball/src/libs/tracker and /cib, including but not limited to the following:

CLAIM 1	HiBall
	/hiball/src/libs/tracker/chooser.cpp /hiball/src/libs/tracker/chooser.h /hiball/src/libs/tracker/flacquire.cpp /hiball/src/libs/tracker/flacquire.h /hiball/src/libs/tracker/acquire.cpp /hiball/src/libs/tracker/acquire.h /hiball/src/libs/tracker/hiballfilter.h /hiball/src/libs/tracker/hiballfilter.cpp /hiball/src/libs/tracker/tracker.cpp /hiball/src/libs/tracker/tracker.h /hiball/src/libs/tracker/ceiling.h /hiball/src/libs/tracker/ceiling.cpp /hiball/src/libs/tracker/smooth.h /hiball/src/libs/tracker/smooth.cpp /hiball/src/libs/cib/cib.h /hiball/src/libs/cib/cib.cpp /hiball/src/libs/cib/hiball.h /hiball/src/libs/cib/hiball.cpp

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CLAIM 1	HiBall
	See also Defendants' Invalidity Contentions for further discussion.
[1.a] an estimation subsystem; and	At least under Plaintiffs' apparent infringement theory, HiBall discloses, either expressly or inherently, an estimation subsystem. In the alternative, this element would be obvious over HiBall in light of the other references disclosed in Defendants' Invalidity Contentions and/or the knowledge of one of ordinary skill in the art. *See, e.g.*: As a result of these improvements the HiBall Tracker can generate over 2000 ***estimates*** per second, with less than one millisecond of latency. The system exhibits sub-millimeter translation noise and similar measured accuracy, as well as less than 0.03 degrees of orientation noise with similar measured accuracy. The weight of the user-worn HiBall is about 300 grams, making it lighter than just one camera in the 1991 system. The working volume of the current system is greater than 90 cubic meters (greater than 45 square meters of floor space, greater than 2 meters of height variation). This area can be expanded by adding more tiles, or by using checkerboard configurations which spread tiles over a larger area. Welch 1999 at 2. Both parts of the camera model are determined using a calibration procedure that relies on a goniometer (an angular positioning system) of our own design. This device consists of two servo motors mounted together such that one motor provides rotation about the vertical axis while the second motor provides rotation about an axis orthogonal to vertical. An important characteristic of the goniometer is that the rotational axes of the two motors intersect at a point at the center of the HiBall optical sphere; this point is defined as the origin of the HiBall. (It is this origin that provides the reference for the HiBall state during run time as described in section 5.3.) The rotational positioning motors were rated to provide 20 arc-second precision; we further calibrated them using a surveying grade theodolite, an angle measuring system, to 6 arc seconds. In order to determine the mapping between sensor image plane coordinates and three-space rays, we use a single LED mounted at a fixed location in the laboratory such that it is centered in the view directly out of the top lens of the HiBall. This ray defines the Z or up axis for the HiBall coordinate system. We sample other rays by rotating the goniometer motors under computer control. We sample each view with rays spaced about every 6 minutes of arc throughout the field of view. We repeat each measurement 100 times in order to reduce the effects of noise on the individual measurements and ***to estimate the standard deviation of the measurements***. Given the tables of approximately 2500 measurements for each view, we first determine a 3 by 4 view matrix using standard linear least-squares techniques. Then we determine the deviation of

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	each measured point from that predicted by the ideal linear model. These deviations are re-sampled into a 25 by 25 grid indexed by sensor-plane coordinates using a simple scan conversion procedure and averaging. Given a measurement from a sensor at run time we convert it to an "ideal" measurement by subtracting a deviation bi-linearly interpolated from the nearest 4 entries in the table. Welch 1999 at 3 The HiBall tracker system (Figure 2) provides six-degree-of freedom tracking of devices in real time. An outward looking infrared-sensing subsystem called a HiBall (Figure 1, lower-right) is mechanically fixed to each device to be tracked. The HiBalls view an environment containing a subsystem of fixed-location infrared beacons which we call the Ceiling. At the present time, the beacons are in fact entirely located in the ceiling of our laboratory, but could as well be located in walls or other arbitrary fixed locations. These subsystems are coordinated by a Ceiling-HiBall Interface Board (CIB) which provides communication and synchronization functions between the host computer and the attached subsystems. Each HiBall has 26 narrow (less than 6 degree) views distributed over a large solid angle. Beacons are selectively flashed in a sequence such that they are seen by many different fields of view of each HiBall. Initial acquisition is performed using a brute force search through beacon space, but once initial lock is made, the selection of beacons to flash is tailored to the fields of view of the HiBalls. Tracking is maintained using a ***Kalman filter-based prediction-correction algorithm known as SCAAT***. This technique has been further extended to provide self-calibration of the Ceiling on-line with the tracking of the attached HiBalls. Welch 1999 at 2. 4.2 The HiBall As can be seen in Figure 1 and color plate image Welch 1 the HiBall is a hollow ball having dodecahedral symmetry with lenses in the upper six faces and lateral effect photo diodes (LEPDs) on the insides of the opposing six lower faces. This immediately gives six primary fields of view, or camera systems which share the same internal air space, and whose adjacent directions of view are uniformly separated by 57 degrees. While the original intent of the shared internal air space was to save space, we subsequently realized that light entering any lens sufficiently off axis can be seen by an adjacent LEPD. As such, five secondary fields of view are provided by the top or central lens, and three secondary fields of view are provided by the five other lenses. Overall, this provides 26 fields of view which are used to sense widely separated groups of beacons in the environment. While these extra views complicate the initialization of the Kalman filter as described in section 5.5, they turn out to be of great benefit during steady-state tracking by effectively increasing the overall HiBall field of view without sacrificing resolution. Welch 1999 at 2-3.

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	4.3 The Ceiling-HiBall Interface Board The Ceiling-HiBalI Interface Board (CIB), shown below in Figure 4, provides communication and synchronization between a host personal computer, the Ceiling (section 4.1) and the HiBall (section 4.2). The CIB has four Ceiling ports allowing interleaving of ceiling panels for up to four simultaneous led flashes and/or higher Ceiling bandwidth for more simultaneous hiball usage. (The Ceiling bandwidth is inherently limited by LED current restrictions as described in section 4.1, but this can be increased by spatially multiplexing the Ceiling tiles.) The CIB has two tether interfaces that can communicate with up to four daisy-chained hiballs each. The full-duplex communication with the hiballs uses a modulation scheme (BPSK) allowing future wireless operation. The interface from the CIB to the host PC is the stable IEEE1284C extended parallel port (EPP) standard. The CIB comprises analog drive and receive components as well as digital logic components. The digital components implement store and forward in both directions and synchronize the timing of the LED "on" interval within the HiBall dark-light-dark intervals. The protocol supports fullduplex flow control. The data are arranged into packets containing error detection to insure data quality. Welch 1999 at 3. **The HiBall-3000 Optical Sensor** The HiBall-3000 tracker system is composed of two key integrated components; the HiBall Optical Sensor and the HiBall Ceiling Beacon Arrays. The HiBall Optical Sensor is composed of 6 lenses and photodiodes arranged so that each photodiode can 'view' infrared LEDs, in the Beacon Arrays mounted on the ceiling, through several of the 6 lenses. The assembly includes signal processing and analog-to-digital conversion circuitry. The total weight is about 6 ounces, making it light enough to comfortably mount on a headmounted display or hand-held device. By locating the sensors on the person or object being tracked — *inside-out tracking* — sensitivity around the working area is increased and the tracker area scales almost without limit. An entire lab, movie set, or assembly area can be tracked. The HiBall can also be mounted on a small probe or stylus, enabling extremely accurate measurements of individual objects within a large space. For example, this can be used for very rapid measurement of actual television or movie sets or other real-world objects to be combined with virtual scenes. No other device can provide comparable speed and accuracy over a wide area. 3rdTech at 1. **HiBall Beacon Array Modules** The infrared LEDs 'seen' by the HiBall Sensor are embedded in a series of ceiling mounted strips forming a 2D Beacon Array - 8 LEDs per strip; 6 strips per Beacon Array Module (BAM). These strips are designed to slip easily

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	into a typical 'drop ceiling' with no changes required in panels, lights, vents, etc. - the more BAMs employed, the greater the range of the tracker. The arrays are highly modular — available in configurations covering as little as 64 square feet (8' x 8') or more than 1,600 square feet (40' x 40'). And no special adjustments are required to the ceiling structure — the system's precision is unaffected by typical variations in ceiling height. The HiBall Sensor and the Beacon Arrays are synchronized by a Ceiling- HiBall Interface Board (CIB), part of the system's integrated PC, which enables extremely high rates of LED 'sightings'— approximately 2,000 per second. This results in a tracker update rate of 2,000 Hz — several times faster than other commercially available wide-area trackers. Faster updates means lower latency and more accurate tracking - even with rapid movements. **AutoCalibration** The system makes use of a *single constraint at a time* (SCAAT) algorithm to compute the location and orientation of the HiBall Sensor at every LED sighting. In addition, the system incorporates *auto-calibration* — tuning the modeled location of individual LEDs on every update. This accommodates typical shifts and movements in the ceiling tiles and BAMs without loss of accuracy or performance. **Applications** The range and performance of the HiBall-3000 Tracker open up new possibilities for large-scale virtual reality such as exploring full-size architectural designs or engineering prototypes. Its precision enables largescale augmented reality for applications in medicine, training and entertainment where accurate correspondence between physical reality and the virtual world are critical. **Proven Results** Developed in the Computer Science Department of the University of North Carolina at Chapel Hill (see www.cs.unc.edu/~tracker), the original HiBall tracker has been in use since 1997 and has consistently exceeded performance expectations. 3rdTech at 1. **The SCAAT algorithm** The UNC HiBall Tracker relies on the SCAAT (Single Constraint At A Time) algorithm to compute the user's position and orientation from the individual sightings the HiBall makes of LEDs on the ceiling panels. The algorithm makes innovative use of an Extended Kalman Filter to provide position and orientation updates after each individual LED sighting, rather than after a group of several sightings as in the previous generation of UNC ceiling tracker. In addition, SCAAT improves on previously developed auto calibration techniques to allow on-line calibration as described below. For more information see Greg Welch's SCAAT page which includes links to

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	Greg Welch and Gary Bishop's 1997 SIGGRAPH paper on SCAAT. UNC HiBall Tracker at 2. **Autocalibration** The current ceiling's lower cost design was made possible by an auto calibration process described in Gottschalk93. The SCAAT algorithm improves on this by allowing auto calibration, tuning the actual LED positions, to be performed while the system is tracking. This accommodates shifts in the tiles and LEDs which can occur during normal use. In addition this technique opens possibilities for even less initial knowledge of LED placement than the current ceiling provides. As a test and demonstration of the autocalibration abilities of SCAAT, we have intentionally raised ceiling panels from their correct position. Here Dr. Gary Bishop is shown making the adjustments. The system was given only the initial flat LED positions, but after less than ten minutes of use (successfully tracking with the misplaced panels), SCAAT had accurately adjusted its knowledge of the LED positions through displacements more than 5cm. The above visualization shows the final measured LED positions. UNC HiBall Tracker at 2-3. **6.2.2 Complete System Simulations.** To produce realistic data for developing and tuning our algorithms we collected several motion paths ***(sequences of pose estimates***) from our first generation electro-optical tracker (Figure 3) at its 70 Hz maximum report rate. These paths were recorded from both naive users visiting our monthly “demo days” and from experienced users in our labs. In the same fashion as we had done for (Azuma & Bishop, 1994a) we filtered the raw path data with a non-causal zero-phase-shift low-pass filter to eliminate energy above 2 Hz. The output of the low-pass filtering was then re-sampled at whatever rate we wanted to run the simulated tracker, usually 1000 Hz. For the purposes of our simulations we considered these resampled paths to be the “truth”—a perfect representation of a user’s motion. Tracking error was determined by comparing the “true” path to the ***estimated path produced by the tracker.*** The simulator reads camera models describing the 26 views, the sensor noise parameters, the LED positions and their expected error, and the motion path described above. Before beginning the simulation, the LED positions are perturbed from their ideal positions by adding normally distributed error to each axis. Then, for each simulated cycle of operation, the “true” pose are updated using the input motion path. Next, a view is chosen and a visible LED within that view is selected, and the image-plane coordinates of the LED on the chosen sensor are computed using the camera model for the view and the LED as described in Section 5.3. These sensor coordinates are then perturbed based on the sensor noise model (Section 6.2.1) using the distance and angle to the LED. Now

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	these noise corrupted sensor readings are fed to the SCAAT filter to produce an updated position estimate. The position estimate is compared to the true position to produce a scalar error metric described next. Welch HiBall at 16-17. **5.4 On-line LED Autocalibration** Along with the benefit of simplicity and speed, the SCAAT approach offers the ***additional capability of being able to estimate the 3D positions of the LEDs*** in the world concurrently with the pose of the HiBall, on line, in real time. This capability is a tremendous benefit in terms of the accuracy and noise characteristics of the estimates. Accurate LED position estimates are so important that prior to the introduction of the SCAAT approach a specialized off-line approach was developed to address the problem (Gottschalk & Hughes, 1993). The method we now use for autocalibration involves defining ***a distinct SCAAT Kalman filter*** for each LED. Specifically, for each LED we maintain a state $\bar{l}$ (***estimate of the 3D position***) and a 3x3 Kalman filter covariance. At the beginning of ***each estimation cycle*** we form an augmented state vector $\hat{x}$ using the appropriate LED state and the current HiBall state: $\hat{x} = [\bar{x}^{\mathrm{T}}, \bar{l}^{\mathrm{T}}]^{\mathrm{T}}$. Similarly we augment ***the Kalman filter error*** covariance matrix with that of the LED filter. We then follow the normal steps outlined in Section 5.3, with the result being that the LED portion of the filter state and covariance is updated in accordance with the measurement residual. At the end of the cycle we extract the LED portions of the state and covariance from the augmented filter, and save them externally. The effect is that as the system is being used, it continually refines its estimates of the LED positions, ***thereby continually improving its estimates of the HiBall pose***. Again, for additional information see (Welch, 1996; Welch & Bishop, 1997). Welch HiBall at 13. The Kalman filter requires both a model of the process dynamics, and a model of the relationship between the process state and the available measurements. In part due to the simplicity of the SCAAT approach we are able to use a simple PV (position-velocity) process model (Brown & Hwang, 1992). Consider the simple example state vector $\bar{x}(t) = [x_p(t), x_v(t)]^{\mathrm{T}}$ where the first element $x_p(t)$ is the pose (position or orientation) and the second element $x_v(t)$ is the corresponding velocity, i.e. $x_v(t) = \frac{d}{dt}x_p(t)$. We model the continuous change in the HiBall state with the simple differential equation $$\frac{d}{dt}\bar{x}(t) = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} x_p(t) \\ x_v(t) \end{bmatrix} + \begin{bmatrix} 0 \\ \mu \end{bmatrix}u(t), \qquad (1)$$

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	where *u(t)* is a normally-distributed white (in the frequency spectrum) scalar noise process, and the scalar μ represents the magnitude or *spectral density* of the noise. We use a similar model with a distinct noise process for each of the six pose elements. We determine the individual noise magnitudes using an off-line simulation of the system and a non-linear optimization strategy that seeks to minimize the variance between the estimated pose and a known motion path. (See Section 6.2.2.) The differential equation (1) represents a continuous integrated random walk, or an integrated *Wiener* or *Brownian-motion* process. Specifically, we model each component of the linear and angular HiBall velocities as a random walk, and then use these (assuming constant inter-measurement velocity) to estimate the HiBall pose at time $t + \delta t$ as follows: $$\bar{x}(t+\delta t) = \begin{bmatrix} 1 & \delta t \\ 0 & 1 \end{bmatrix} \bar{x}(t) \qquad (2)$$ for each of the six pose elements. In addition to a relatively simple process model, the HiBall measurement model is relatively simple. For any Ceiling LED (Section 4.2) and HiBall view (Section 4.1), the 2D sensor measurement can be modeled as $$\begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} c_x / c_z \\ c_y / c_z \end{bmatrix} \qquad (3)$$ where $$\begin{bmatrix} c_x \\ c_y \\ c_z \end{bmatrix} = VR^{\mathrm{T}}(\hat{l}_{xyz} - \bar{x}_{xyz}), \qquad (4)$$ is the camera viewing matrix from Section 5.1, is the position of the LED in the world, is the position of the HiBall in the world, and is a rotation matrix corresponding to the orientation of the HiBall in the world. In practice we maintain the orientation of the HiBall as a combination of a global (external to the state) quaternion and a set of incremental angles as described in (Welch, 1996; Welch & Bishop, 1997). Welch HiBall at 11-12. **5.2 On-Line HiBall Measurements** Upon receiving a command from the CIB (Section 4.3), which is synchronized with a CIB command to the ceiling, the HiBall selects the specified LEPD and performs three measurements, one before the LED flashes, one during the LED flash, and one after the LED flash. Known as “dark-light-dark”, this technique is used to subtract

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	out DC bias, low frequency noise, and background light from the LED signal. We then convert the measured sensor coordinates to "ideal" coordinates using the calibration tables described in Section 5.1. In addition, during run time we attempt to maximize the signal-to-noise ratio of the measurement with an automatic gain control scheme. For each LED we store a target signal strength factor. We compute the LED current and number of integrations (of successive accumulated A/D samples) by dividing this strength factor by the square of the distance to the LED, estimated from the current position estimate. After a reading we look at the strength of the actual measurement. If it is larger than expected we reduce the gain, if it is less than expected we increase the gain. The increase and decrease are implemented as on-line averages with scaling such that the gain factor decreases rapidly (to avoid overflow) and increases slowly. Finally we use the measured signal strength to estimate the noise on the signal using (Chi, 1995), and then ***use this as the measurement noise estimate for the Kalman filter*** (Section 5.3). Welch HiBall at 9-10. **1.3 The HiBall Tracking System** In this article we describe a new and vastly improved version of the 1991 system. We call the new system the *HiBall Tracking System*. Thanks to significant improvements in hardware and software this HiBall system offers unprecedented speed, resolution, accuracy, robustness, and flexibility. The bulky and heavy sensors and backpack of the previous system have been replaced by a small *HiBall* unit (Figure 4, bottom). In addition, the precisely machined LED ceiling panels of the previous system have been replaced by looser-tolerance panels that are relatively inexpensive to make and simple to install (Figure 4, top; Figure 10). Finally, we are using an unusual Kalman-filter-based algorithm that ***generates very accurate pose estimates*** at a high rate with low latency, and simultaneously self-calibrates the system. As a result of these improvements the HiBall Tracking System can generate over 2000 pose estimates per second, with less than one millisecond of latency, better than 0.5 millimeters and 0.03 degrees of absolute error and noise, everywhere in a 4.5 by 8.5 meter room (with over two meters of height variation). The area can be expanded by adding more panels, or by using checkerboard configurations which spread panels over a larger area. The weight of the user-worn HiBall is about 300 grams, making it lighter than one optical sensor in the 1991 system. Multiple HiBall units can be daisy chained together for head or hand tracking, pose-aware input devices, or precise 3D point. Welch HiBall at 4.

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	The HiBall The HiBall is a cluster of 6 lenses and 6 photodiodes arranged so that each photodiodes can view LEDs through several of the 6 lenses, providing 26 view frustra originating at the HiBall. The assembly will include signal processing and A/D conversion circuitry. The total weight is about 5 ounces, making it lighter than just one of the cameras in the previous generation ceiling tracker. The HiBall and the ceiling panel are synchronized by a custom interface board which allows very high rate of LED sightings. The hardware alone can perform more than 3,000 sightings per second, while the whole system tracks using about 1,500. UNC HiBall Tracker at 1. *See also* /hiball/src/libs/tracker and /cib, including but not limited to the following: /hiball/src/libs/tracker/chooser.cpp /hiball/src/libs/tracker/chooser.h, including ll. 8-11 ("The job of the chooser is to pick which LED and which view to use for the next sample. It does this by projected the image plane of views onto the ceiling until it gets one which has /hiball/src/libs/tracker/flacquire.cpp /hiball/src/libs/tracker/flacquire.h, including 7-11 ("Acquire's job is to locate the hiball well enough that a Kalman Filter can be started which converges on the position. The initial location is done with search the ceiling for any sighted LED and then a series of steps to disambiguate the sighting (between shared views).") /hiball/src/libs/tracker/acquire.cpp /hiball/src/libs/tracker/acquire.h /hiball/src/libs/tracker/hiballfilter.h, including ll. 7-10 ("HiballFilter is the implementation of a Kalman Filter. It is given readings by Tracker and keeps a state of the hiball's pose. It also uses and updates estimated LED positions from the Ceiling.")

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	/hiball/src/libs/tracker/hiballfilter.cpp /hiball/src/libs/tracker/smooth.h, ll. 6-7 ("gets a number of tracker states, puts them into a circular buffer then does a noncausal filter, and reprojects to better calculate residuals") /hiball/src/libs/tracker/smooth.cpp /hiball/src/libs/cib/cib.h /hiball/src/libs/cib/cib.cpp *See also* Defendants' Invalidity Contentions for further discussion.
[1.b] a sensor subsystem coupled to the estimation subsystem and configured to provide configuration data to the estimation subsystem and to provide measurement information to the estimation subsystem for localizing an object;	At least under Plaintiffs' apparent infringement theory, HiBall discloses, either expressly or inherently, a sensor subsystem coupled to the estimation subsystem and configured to provide configuration data to the estimation subsystem and to provide measurement information to the estimation subsystem for localizing an object. In the alternative, this element would be obvious over HiBall in light of the other references disclosed in Defendants' Invalidity Contentions and/or the knowledge of one of ordinary skill in the art. *See, e.g.*: As a result of these improvements the HiBall Tracker can generate over 2000 estimates per second, with less than one millisecond of latency. The system exhibits sub-millimeter translation noise and similar measured accuracy, as well as less than 0.03 degrees of orientation noise with similar measured accuracy. The weight of the user-worn HiBall is about 300 grams, making it lighter than just one camera in the 1991 system. The working volume of the current system is greater than 90 cubic meters (greater than 45 square meters of floor space, greater than 2 meters of height variation). This area can be expanded by adding more tiles, or by using checkerboard configurations which spread tiles over a larger area. Welch 1999 at 2. Both parts of the camera model are determined using a calibration procedure that relies on a goniometer (an angular positioning system) of our own design. This device consists of two servo motors mounted together such that one motor provides rotation about the vertical axis while the second motor provides rotation about an axis orthogonal to

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	vertical. An important characteristic of the goniometer is that the rotational axes of the two motors intersect at a point at the center of the HiBall optical sphere; this point is defined as the origin of the HiBall. (It is this origin that provides the reference for the HiBall state during run time as described in section 5.3.) The rotational positioning motors were rated to provide 20 arc-second precision; we further calibrated them using a surveying grade theodolite, an angle measuring system, to 6 arc seconds. In order to determine the mapping between sensor image plane coordinates and three-space rays, we use a single LED mounted at a fixed location in the laboratory such that it is centered in the view directly out of the top lens of the HiBall. This ray defines the Z or up axis for the HiBall coordinate system. We sample other rays by rotating the goniometer motors under computer control. We sample each view with rays spaced about every 6 minutes of arc throughout the field of view. We repeat each measurement 100 times in order to reduce the effects of noise on the individual measurements and to estimate the standard deviation of the measurements. Given the tables of approximately 2500 measurements for each view, we first determine a 3 by 4 view matrix using standard linear least-squares techniques. Then we determine the deviation of each measured point from that predicted by the ideal linear model. These deviations are re-sampled into a 25 by 25 grid indexed by sensor-plane coordinates using a simple scan conversion procedure and averaging. Given a measurement from a sensor at run time we convert it to an “ideal” measurement by subtracting a deviation bi-linearly interpolated from the nearest 4 entries in the table. Welch 1999 at 3 The HiBall tracker system (Figure 2) provides six-degree-of freedom tracking of devices in real time. An outward looking infrared-sensing subsystem called a HiBall (Figure 1, lower-right) is mechanically fixed to each device to be tracked. The HiBalls view an environment containing a subsystem of fixed-location infrared beacons which we call the Ceiling. At the present time, the beacons are in fact entirely located in the ceiling of our laboratory, but could as well be located in walls or other arbitrary fixed locations. These subsystems are coordinated by a Ceiling-HiBall Interface Board (CIB) which provides communication and synchronization functions between the host computer and the attached subsystems. Each HiBall has 26 narrow (less than 6 degree) views distributed over a large solid angle. Beacons are selectively flashed in a sequence such that they are seen by many different fields of view of each HiBall. Initial acquisition is performed using a brute force search through beacon space, but once initial lock is made, the selection of beacons to flash is tailored to the fields of view of the HiBalls. Tracking is maintained using a Kalman filter-based prediction-correction algorithm known as SCAAT. This technique has been further extended to provide self-calibration of the Ceiling on-line with the tracking of the attached HiBalls. Welch 1999 at 2. 4.2 The HiBall

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	As can be seen in Figure 1 and color plate image Welch 1 the HiBall is a hollow ball having dodecahedral symmetry with lenses in the upper six faces and lateral effect photo diodes (LEPDs) on the insides of the opposing six lower faces. This immediately gives six primary fields of view, or camera systems which share the same internal air space, and whose adjacent directions of view are uniformly separated by 57 degrees. While the original intent of the shared internal air space was to save space, we subsequently realized that light entering any lens sufficiently off axis can be seen by an adjacent LEPD. As such, five secondary fields of view are provided by the top or central lens, and three secondary fields of view are provided by the five other lenses. Overall, this provides 26 fields of view which are used to sense widely separated groups of beacons in the environment. While these extra views complicate the initialization of the Kalman filter as described in section 5.5, they turn out to be of great benefit during steady-state tracking by effectively increasing the overall HiBall field of view without sacrificing resolution. Welch 1999 at 2-3. 4.3 The Ceiling-HiBall Interface Board The Ceiling-HiBalI Interface Board (CIB), shown below in Figure 4, provides communication and synchronization between a host personal computer, the Ceiling (section 4.1) and the HiBall (section 4.2). The CIB has four Ceiling ports allowing interleaving of ceiling panels for up to four simultaneous led flashes and/or higher Ceiling bandwidth for more simultaneous hiball usage. (The Ceiling bandwidth is inherently limited by LED current restrictions as described in section 4.1, but this can be increased by spatially multiplexing the Ceiling tiles.) ***The CIB has two tether interfaces that can communicate with up to four daisy-chained hiballs each***. The full-duplex communication with the hiballs uses a modulation scheme (BPSK) allowing future wireless operation. ***The interface from the CIB to the host PC is the stable IEEE1284C extended parallel port (EPP) standard***. The CIB comprises analog drive and receive components as well as digital logic components. The digital components implement store and forward in both directions and synchronize the timing of the LED "on" interval within the HiBall dark-light-dark intervals. The protocol supports fullduplex flow control. The data are arranged into packets containing error detection to insure data quality. Welch 1999 at 3. **The HiBall-3000 Optical Sensor** The HiBall-3000 tracker system is composed of two key integrated components; ***the HiBall Optical Sensor and the HiBall Ceiling Beacon Arrays***. The HiBall Optical Sensor is composed of 6 lenses and photodiodes arranged so that each photodiode can 'view' infrared LEDs, in the Beacon Arrays mounted on the ceiling, through several of the 6 lenses. The assembly includes signal processing and analog-to-digital conversion circuitry. The total weight is

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	about 6 ounces, making it light enough to comfortably mount on a headmounted display or hand-held device. By locating t***he sensors on the person or object being tracked — inside-out tracking*** — sensitivity around the working area is increased and the tracker area scales almost without limit. An entire lab, movie set, or assembly area can be tracked. The HiBall can also be mounted on a small probe or stylus, enabling extremely accurate measurements of individual objects within a large space. For example, this can be used for very rapid measurement of actual television or movie sets or other real-world objects to be combined with virtual scenes. No other device can provide comparable speed and accuracy over a wide area. 3rdTech at 1. **HiBall Beacon Array Modules** The infrared LEDs 'seen' by the HiBall Sensor are embedded in a series of ceiling mounted strips forming a 2D Beacon Array - 8 LEDs per strip; 6 strips per Beacon Array Module (BAM). These strips are designed to slip easily into a typical 'drop ceiling' with no changes required in panels, lights, vents, etc. - the more BAMs employed, the greater the range of the tracker. The arrays are highly modular — available in configurations covering as little as 64 square feet (8' x 8') or more than 1,600 square feet (40' x 40'). And no special adjustments are required to the ceiling structure — the system's precision is unaffected by typical variations in ceiling height. The HiBall Sensor and the Beacon Arrays are synchronized by a Ceiling- ***HiBall Interface Board (CIB)***, part of the system's integrated PC, which enables extremely high rates of LED 'sightings'— approximately 2,000 per second. This results in a tracker update rate of 2,000 Hz — several times faster than other commercially available wide-area trackers. Faster updates means lower latency and more accurate tracking - even with rapid movements. **AutoCalibration** The system makes use of a *single constraint at a time* (SCAAT) algorithm to compute the location and orientation of the HiBall Sensor at every LED sighting. In addition, the system incorporates *auto-calibration* — tuning the modeled location of individual LEDs on every update. This accommodates typical shifts and movements in the ceiling tiles and BAMs without loss of accuracy or performance. **Applications** The range and performance of the HiBall-3000 Tracker open up new possibilities for large-scale virtual reality such as exploring full-size architectural designs or engineering prototypes. Its precision enables largescale augmented reality for applications in medicine, training and entertainment where accurate correspondence between physical reality and the virtual world are critical. **Proven Results**

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	Developed in the Computer Science Department of the University of North Carolina at Chapel Hill (see www.cs.unc.edu/~tracker), the original HiBall tracker has been in use since 1997 and has consistently exceeded performance expectations. 3rdTech at 1. **3. SYSTEM OVERVIEW** The HiBall Tracking System consists of three main components (Figure 6). An outward-looking sensing unit we call the *HiBall* is fixed to each user to be tracked. The HiBall unit observes a subsystem of fixed-location infrared LEDs we call the *Ceiling* 1. Communication and synchronization between the host computer and these subsystems is coordinated by the **Ceiling-HiBall Interface Board (CIB). I**n Section 4 we describe these components in more detail. Each HiBall observes LEDs through multiple sensor-lens *views* that are distributed over a large solid angle. LEDs are sequentially flashed (one at a time) such that they are seen via a diverse set of views for each HiBall. Initial *acquisition* is performed using a brute force search through LED space, but once initial lock is made, the selection of LEDs to flash is tailored to the views of the active HiBall units. Pose estimates are maintained using a Kalman-filter-based prediction-correction approach known as *single-constraint-at-a-time* or SCAAT tracking. This technique has been extended to provide self-calibration of the Ceiling, concurrent with HiBall tracking. In Section 5 we describe the methods we employ, including the initial acquisition process and the SCAAT approach to pose estimation, with the *autocalibration* extension. Welch HiBall at 6.

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	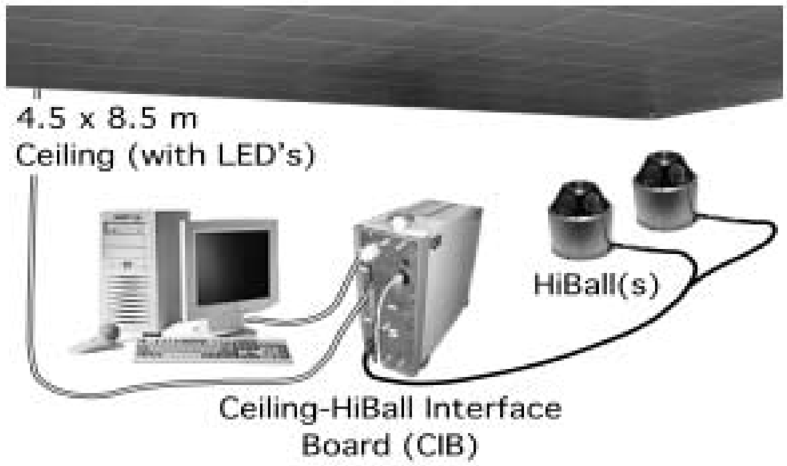 **Figure 6** Welch HiBall at Fig. 6. **4.3 The Ceiling-HiBall Interface Board** ***The Ceiling-HiBall Interface Board or CIB (Figure 11) provides communication and synchronization*** between a host personal computer, the HiBall (Section 4.1), and the Ceiling (Section 4.2). The CIB has four Ceiling ports allowing interleaving of ceiling panels for up to four simultaneous LED flashes and/or higher Ceiling bandwidth. (The Ceiling bandwidth is inherently limited by LED power restrictions as described in Section 4.2, but this can be increased by spatially multiplexing the Ceiling panels.) ***The CIB has two tether interfaces that can communicate with up to four daisy-chained HiBall units. The full-duplex communication with the HiBall units uses a modulation scheme (BPSK) allowing future wireless operation. The interface from the CIB to the host PC is the stable IEEE1284C extended parallel port (EPP) standard.*** The CIB comprises analog drive and receive components as well as digital logic components. The digital components implement store and forward in both directions and synchronize the timing of the LED "on" interval within the HiBall dark-light-dark intervals (Section 5.2). The protocol supports full-duplex flow control. The data are arranged into packets that incorporate error detection. Welch HiBall at 8-9.

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CLAIM 1	HiBall
	4. SYSTEM COMPONENTS **4.1 The HiBall** The original electro-optical tracker (Figure 3, bottom) used independently housed lateral effect photo-diode units (LEPDs) attached to a light-weight tubular framework. As it turns out, the mechanical framework would flex (distort) during use, contributing to estimation errors. In part to address this problem the HiBall sensor unit was designed as a single rigid hollow ball having dodecahedral symmetry, with lenses in the upper six faces and LEPD on the insides of the opposing six lower faces (Figure 7). This immediately gives six primary "camera" *views* uniformly spaced by 57 degrees. The views efficiently share the same internal air space, and are rigid with respect to each other. In addition, light entering any lens sufficiently off axis can be seen by a neighboring LEPD, giving rise to five secondary views through the top or central lens, and three secondary views through the five other lenses. Overall, this provides 26 fields of view which are used to sense widely separated groups of LEDs in the environment. While the extra views complicate the initialization of the Kalman filter as described in Section 5.5, they turn out to be of great benefit during steady-state tracking by effectively increasing the overall HiBall field of view without sacrificing optical sensor resolution. The lenses are simple plano-convex fixed-focus lenses. Infrared (IR) filtering is provided by fabricating the lenses themselves from RG-780 Schott glass filter material which is opaque to better than 0.001% for all visible wavelengths, and transmissive to better than 99% for IR wavelengths longer than 830 nm. The longwave filtering limit is provided by the DLS-4 LEPD silicon photodetector (UDT Sensors, Inc.) with peak responsivity at 950 nm but essentially blind above 1150 nm. The LEPDs themselves are not imaging devices; rather they detect the centroid of the luminous flux incident on the detector. The x-position of the centroid determines the ratio of two output currents, while the y-position determines the ratio of two other output currents. The total output current of each pair are commensurate, and proportional to the total incident flux. Consequently, focus is not an issue, so the simple fixed-focus lenses work well over a range of LED distances from about half a meter to infinity. The LEPDs and associated electronic components are mounted on a custom rigid-flex printed circuit board (Figure 8). This arrangement makes efficient use of the internal HiBall volume while maintaining isolation between analog and digital circuitry, and increasing reliability by alleviating the need for inter-component mechanical connectors. Figure 9 shows the physical arrangement of the folded electronics in the HiBall. Each LEPD has four transimpedance amplifiers (shown together as one "Amp" in Figure 9), the analog outputs of which are multiplexed with those of the other LEPDs, then sampled, held, and converted by four 16-bit Delta-Sigma analog-

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CLAIM 1	HiBall
	to-digital (A/D) converters. Multiple samples are integrated via an accumulator. The digitized LEPD data are organized into packets for communication back to the CIB. The packets also contain information to assist in error-detection. The communication protocol is simple, and while presently implemented by wire, the modulation scheme is amenable to a wireless implementation. The present wired implementation allows multiple HiBall units to be daisy-chained so a single cable can support a user with multiple HiBall units. Welch HiBall at 6-7. **1.3 The HiBall Tracking System** In this article we describe a new and vastly improved version of the 1991 system. We call the new system the *HiBall Tracking System*. Thanks to significant improvements in hardware and software this HiBall system offers unprecedented speed, resolution, accuracy, robustness, and flexibility. The bulky and heavy sensors and backpack of the previous system have been replaced by a small *HiBall* unit (Figure 4, bottom). In addition, the precisely machined LED ceiling panels of the previous system have been replaced by looser-tolerance panels that are relatively inexpensive to make and simple to install (Figure 4, top; Figure 10). Finally, we are using an unusual Kalman-filter-based algorithm that generates very accurate pose estimates at a high rate with low latency, and simultaneously self-calibrates the system. As a result of these improvements the HiBall Tracking System can generate over 2000 pose estimates per second, with less than one millisecond of latency, better than 0.5 millimeters and 0.03 degrees of absolute error and noise, everywhere in a 4.5 by 8.5 meter room (with over two meters of height variation). The area can be expanded by adding more panels, or by using checkerboard configurations which spread panels over a larger area. The weight of the user-worn HiBall is about 300 grams, making it lighter than one optical sensor in the 1991 system. Multiple HiBall units can be daisy chained together for head or hand tracking, pose-aware input devices, or precise 3D point. Welch HiBall at 4. The HiBall tracking system resolves linear motion of less than 0.2mm and angular motions under 0.03 degrees without the distortion seen in magnetic trackers. The update rate is greater than 1500 Hz and latency is about 1ms. To our knowledge, this was the first and remains the only demonstrated scalable tracking system for HMDs. UNC HiBall Tracker at 1. **The HiBall**

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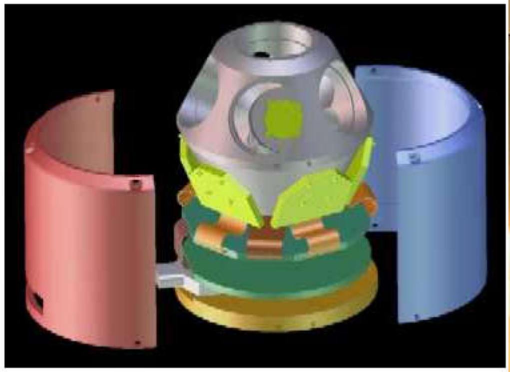
	The HiBall is a cluster of 6 lenses and 6 photodiodes arranged so that each photodiodes can view LEDs through several of the 6 lenses, providing 26 view frustra originating at the HiBall. The assembly will include signal processing and A/D conversion circuitry. The total weight is about 5 ounces, making it lighter than just one of the cameras in the previous generation ceiling tracker. The HiBall and the ceiling panel are synchronized by a custom interface board which allows very high rate of LED sightings. The hardware alone can perform more than 3,000 sightings per second, while the whole system tracks using about 1,500. UNC HiBall Tracker at 1. **The Hiball** (Shown without lenses)   UNC HiBall Tracker at 2. **The SCAAT algorithm** The UNC HiBall Tracker relies on the SCAAT (Single Constraint At A Time) algorithm to compute the user's position and orientation from the individual sightings the HiBall makes of LEDs on the ceiling panels. The algorithm makes innovative use of an Extended Kalman Filter to provide position and orientation updates after each individual LED sighting, rather than after a group of several sightings as in the previous generation of UNC ceiling tracker. In addition, SCAAT improves on previously developed auto calibration techniques to allow on-line calibration as described below. For more information see Greg Welch's SCAAT page which includes links to

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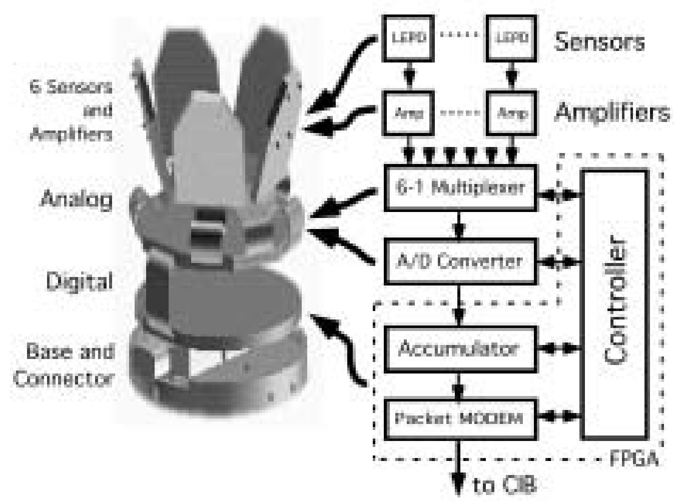
CLAIM 1	HiBall
	Greg Welch and Gary Bishop's 1997 SIGGRAPH paper on SCAAT. UNC HiBall Tracker at 2. **Autocalibration** The current ceiling's lower cost design was made possible by an auto calibration process described in Gottschalk93. The SCAAT algorithm improves on this by allowing auto calibration, tuning the actual LED positions, to be performed while the system is tracking. This accommodates shifts in the tiles and LEDs which can occur during normal use. In addition this technique opens possibilities for even less initial knowledge of LED placement than the current ceiling provides. As a test and demonstration of the autocalibration abilities of SCAAT, we have intentionally raised ceiling panels from their correct position. Here Dr. Gary Bishop is shown making the adjustments. The system was given only the initial flat LED positions, but after less than ten minutes of use (successfully tracking with the misplaced panels), SCAAT had accurately adjusted its knowledge of the LED positions through displacements more than 5cm. The above visualization shows the final measured LED positions. UNC HiBall Tracker at 2-3.  **Figure 9**

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CLAIM 1	HiBall
	Welch HiBall at Fig. 9. **4.2 The Ceiling** As presently implemented, the infrared LEDs are packaged in 61 centimeter square *panels*, to fit a standard false ceiling grid (Figure 10, top). Each panel uses five printed circuit boards: a main controller board and four identical transverse-mounted *strips* (bottom). Each strip is populated with eight LEDs for a total of 32 LEDs per panel. We mount the assembly on top of a metal panel such that the LEDs protrude through 32 corresponding holes. The design results in a Ceiling with a rectangular LED pattern with periods of 7.6 and 15.2 centimeters. This spacing is used for the initial estimates of the LED positions in the lab, then during normal operation the SCAAT algorithm continually refines the LED position estimates (Section 5.4). The SCAAT *autocalibration* not only relaxes design and installation constraints, but provides greater precision in the face of initial and ongoing uncertainty in the Ceiling structure. We currently have enough panels to cover an area approximately 5.5 by 8.5 meters with a total of approximately 3,000 LEDs. 1 The panels are daisy-chained to each other, and panel selection encoding is position (rather than device) dependent. Operational commands are presented to the first panel of the daisy chain. At each panel, if the panel select code is zero the controller decodes and executes the operation; else it decrements the panel select code and passes it along to the next panel (controller). Upon decoding, a particular LED is selected and the LED is energized. The LED brightness (power) is selectable for *automatic gain control* as described in Section 5.2. We currently use Siemens SFH-487P GaAs LEDs which provide both a wide angle radiation pattern and high peak power, emitting at a center wavelength of 880 nm in the near IR. These devices can be pulsed up to 2.0 Amps for a maximum duration of 200 with a 1:50 (on:off) duty cycle. While the current Ceiling architecture allows flashing of only one LED at a time, LEDs may be flashed in any sequence. As such no single LED can be flashed too long or too frequently. We include both hardware and software protection to prevent this. **4.3 The Ceiling-HiBall Interface Board** The Ceiling-HiBall Interface Board or CIB (Figure 11) provides communication and synchronization between a host personal computer, the HiBall (Section 4.1), and the Ceiling (Section 4.2). The CIB has four Ceiling ports allowing interleaving of ceiling panels for up to four simultaneous LED flashes and/or higher Ceiling bandwidth. (The Ceiling bandwidth is inherently limited by LED power restrictions as described in Section 4.2, but this can be increased by spatially multiplexing the Ceiling panels.) The CIB has two tether interfaces that can communicate with up to four daisy-chained HiBall units. The full-duplex communication with the HiBall units uses a modulation scheme (BPSK) allowing future wireless operation. The interface from the CIB to the host PC is the stable IEEE1284C extended parallel port (EPP) standard. The CIB comprises analog drive and receive

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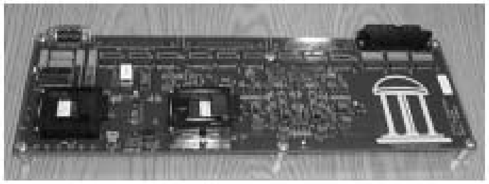
CLAIM 1	HiBall
	components as well as digital logic components. The digital components implement store and forward in both directions and synchronize the timing of the LED "on" interval within the HiBall dark-light-dark intervals (Section 5.2). The protocol supports full-duplex flow control. The data are arranged into packets that incorporate error detection. Welch HiBall at 8-9.  Figure 11 Welch HiBall at Fig. 11. **The SCAAT algorithm** The UNC HiBall Tracker relies on the SCAAT (Single Constraint At A Time) algorithm ***to compute the user's position and orientation from the individual sightings the HiBall makes of LEDs on the ceiling panels. The algorithm makes innovative use of an Extended Kalman Filter*** to provide position and orientation updates after each individual LED sighting, rather than after a group of several sightings as in the previous generation of UNC ceiling tracker. In addition, SCAAT improves on previously developed auto calibration techniques to allow on-line calibration as described below. For more information see Greg Welch's SCAAT page which includes links to Greg Welch and Gary Bishop's 1997 SIGGRAPH paper on SCAAT. UNC HiBall Tracker at 2. **Autocalibration** The current ceiling's lower cost design was made possible by an auto calibration process described in Gottschalk93. ***The SCAAT algorithm improves on this by allowing auto calibration, tuning the actual LED positions, to be performed while the system is tracking.*** This accommodates shifts in the tiles and LEDs which can occur during normal use. In addition this technique opens possibilities for even less initial knowledge of LED placement than the current ceiling provides.

CLAIM 1	HiBall
	As a test and demonstration of the autocalibration abilities of SCAAT, we have intentionally raised ceiling panels from their correct position. Here Dr. Gary Bishop is shown making the adjustments. The system was given only the initial flat LED positions, but after less than ten minutes of use (successfully tracking with the misplaced panels), SCAAT had accurately adjusted its knowledge of the LED positions through displacements more than 5cm. The above visualization shows the final measured LED positions. UNC HiBall Tracker at 2-3. **6.2.2 Complete System Simulations.** To produce realistic data for developing and tuning our algorithms we collected several motion paths *(*sequences of pose estimates) from our first generation electro-optical tracker (Figure 3) at its 70 Hz maximum report rate. These paths were recorded from both naive users visiting our monthly "demo days" and from experienced users in our labs. In the same fashion as we had done for (Azuma & Bishop, 1994a) we filtered the raw path data with a non-causal zero-phase-shift low-pass filter to eliminate energy above 2 Hz. The output of the low-pass filtering was then re-sampled at whatever rate we wanted to run the simulated tracker, usually 1000 Hz. For the purposes of our simulations we considered these resampled paths to be the "truth"—a perfect representation of a user's motion. Tracking error was determined by comparing the "true" path to the estimated path produced by the tracker. The simulator reads camera models describing the 26 views, the sensor noise parameters, the LED positions and their expected error, and the motion path described above. Before beginning the simulation, the LED positions are perturbed from their ideal positions by adding normally distributed error to each axis. Then, for each simulated cycle of operation, the "true" pose are updated using the input motion path. Next, a view is chosen and a visible LED within that view is selected, and the image-plane coordinates of the LED on the chosen sensor are computed using the camera model for the view and the LED as described in Section 5.3. These sensor coordinates are then perturbed based on the sensor noise model (Section 6.2.1) using the distance and angle to the LED. Now these noise corrupted sensor readings are fed to the SCAAT filter to produce an updated position estimate. The position estimate is compared to the true position to produce a scalar error metric described next. Welch HiBall at 16-17. **5.4 On-line LED Autocalibration** Along with the benefit of simplicity and speed, the SCAAT approach offers the additional capability of being able to estimate the 3D positions of the LEDs in the world concurrently with the pose of the HiBall, on line, in real time. This capability is a tremendous benefit in terms of the accuracy and noise characteristics of the estimates. Accurate LED position estimates are so important that prior to the introduction of the SCAAT approach a specialized off-line approach was developed to address the problem (Gottschalk & Hughes, 1993).

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CLAIM 1	HiBall
	The method we now use for autocalibration involves ***defining a distinct SCAAT Kalman filter for each LED.*** Specifically, for each LED we maintain a state $\bar{l}$ (estimate of the 3D position) and a 3x3 Kalman filter covariance. At the beginning of each estimation cycle we form an augmented state vector $\hat{x}$ using the appropriate LED state and the current HiBall state: $\hat{x} = [\bar{x}^{T}, \bar{l}^{T}]^{T}$. Similarly we augment the Kalman filter error covariance matrix with that of the LED filter. We then follow the normal steps outlined in Section 5.3, with the result being that the LED portion of the filter state and covariance is updated in accordance with the measurement residual. At the end of the cycle we extract the LED portions of the state and covariance from the augmented filter, and save them externally. The effect is that as the system is being used, it continually refines its estimates of the LED positions, thereby continually improving its estimates of the HiBall pose. Again, for additional information see (Welch, 1996; Welch & Bishop, 1997). Welch HiBall at 13. The Kalman filter requires both a model of the process dynamics, and a model of the relationship between the process state and the available measurements. In part due to the simplicity of the SCAAT approach we are able to use a simple PV (position-velocity) process model (Brown & Hwang, 1992). Consider the simple example state vector $\bar{x}(t) = [x_p(t), x_v(t)]^{T}$ where the first element $x_p(t)$ is the pose (position or orientation) and the second element $x_v(t)$ is the corresponding velocity, i.e. $x_v(t) = \frac{d}{dt} x_p(t)$. We model the continuous change in the HiBall state with the simple differential equation $$\frac{d}{dt}\bar{x}(t) = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x_p(t) \\ x_v(t) \end{bmatrix} + \begin{bmatrix} 0 \\ \mu \end{bmatrix} u(t), \qquad (1)$$ where *u(t)* is a normally-distributed white (in the frequency spectrum) scalar noise process, and the scalar μ represents the magnitude or *spectral density* of the noise. We use a similar model with a distinct noise process for each of the six pose elements. We determine the individual noise magnitudes using an off-line simulation of the system and a non-linear optimization strategy that seeks to minimize the variance between the estimated pose and a known motion path. (See Section 6.2.2.) The differential equation (1) represents a continuous integrated random walk, or an integrated *Wiener* or *Brownian-motion* process. Specifically, we model each component of the linear and angular HiBall velocities as a random walk, and then use these (assuming constant inter-measurement velocity) to estimate the HiBall pose at time $t + \delta t$ as follows:

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	$$\bar{x}(t+\delta t) = \begin{bmatrix} 1 & \delta t \\ 0 & 1 \end{bmatrix} \bar{x}(t) \qquad (2)$$ for each of the six pose elements. In addition to a relatively simple process model, the HiBall measurement model is relatively simple. For any Ceiling LED (Section 4.2) and HiBall view (Section 4.1), the 2D sensor measurement can be modeled as $$\begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} c_x/c_z \\ c_y/c_z \end{bmatrix} \qquad (3)$$ where $$\begin{bmatrix} c_x \\ c_y \\ c_z \end{bmatrix} = VR^{T}(\hat{l}_{xyz} - \bar{x}_{xyz}), \qquad (4)$$ is the camera viewing matrix from Section 5.1, is the position of the LED in the world, is the position of the HiBall in the world, and is a rotation matrix corresponding to the orientation of the HiBall in the world. In practice we maintain the orientation of the HiBall as a combination of a global (external to the state) quaternion and a set of incremental angles as described in (Welch, 1996; Welch & Bishop, 1997). Welch HiBall at 11-12. **5.2 On-Line HiBall Measurements** Upon receiving a command from the CIB (Section 4.3), which is synchronized with a CIB command to the ceiling, the HiBall selects the specified LEPD and performs three measurements, one before the LED flashes, one during the LED flash, and one after the LED flash. Known as "dark-light-dark", this technique is used to subtract out DC bias, low frequency noise, and background light from the LED signal. We then convert the measured sensor coordinates to "ideal" coordinates using the calibration tables described in Section 5.1. In addition, during run time we attempt to maximize the signal-to-noise ratio of the measurement with an automatic gain control scheme. For each LED we store a target signal strength factor. We compute the LED current and number of integrations (of successive accumulated A/D samples) by dividing this strength factor by the square of the distance to the LED, estimated from the current position estimate. After a reading we look at the strength of the actual measurement. If it is larger than expected we reduce the gain, if it is less than expected we increase the gain. The increase and decrease are implemented as on-line averages with scaling such that the gain

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	factor decreases rapidly (to avoid overflow) and increases slowly. Finally we use the measured signal strength to estimate the noise on the signal using (Chi, 1995), and then use this as the measurement noise estimate for the Kalman filter (Section 5.3). Welch HiBall at 9-10. *See also* /hiball/src/libs/tracker and /cib, including but not limited to the following: /hiball/src/libs/tracker/ceiling.cpp /hiball/src/libs/tracker/ceiling.h /hiball/src/libs/tracker/tracker.h /hiball/src/libs/tracker/tracker.cpp /hiball/src/libs/cib/cib.h /hiball/src/libs/cib/cib.cpp /hiball/src/libs/tracker/hiballfilter.h /hiball/src/libs/tracker/hiballfilter.cpp *See also* Defendants' Invalidity Contentions for further discussion.
[1.c] wherein the estimation subsystem is configured to update a location estimate for the object based on configuration data and measurement information accepted	At least under Plaintiffs' apparent infringement theory, HiBall discloses, either expressly or inherently, wherein the estimation subsystem is configured to update a location estimate for the object based on configuration data and measurement information accepted from the sensor subsystem. In the alternative, this element would be obvious over HiBall in light of the other references disclosed in Defendants' Invalidity Contentions and/or the knowledge of one of ordinary skill in the art. *See, e.g.*:

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CLAIM 1	HiBall
from the sensor subsystem.	As a result of these improvements the HiBall Tracker can generate over 2000 estimates per second, with less than one millisecond of latency. The system exhibits sub-millimeter translation noise and similar measured accuracy, as well as less than 0.03 degrees of orientation noise with similar measured accuracy. The weight of the user-worn HiBall is about 300 grams, making it lighter than just one camera in the 1991 system. The working volume of the current system is greater than 90 cubic meters (greater than 45 square meters of floor space, greater than 2 meters of height variation). This area can be expanded by adding more tiles, or by using checkerboard configurations which spread tiles over a larger area. Welch 1999 at 2. ***This single measurement is compared with a prediction obtained using (2), and the difference or residual is used to update the filter state and covariances using the Kalman gain matrix.*** The Kalman gain is computed as a combination of the current filter covariance, the measurement noise variance (section 6.2. l), and the Jacobian of the measurement model. A more detailed discussion of the HiBall Kalman filter and the SCAAT approach is beyond the scope of this paper. For additional information see [28,29]. Welch 1999 at 4-5. Both parts of the camera model are determined using a calibration procedure that relies on a goniometer (an angular positioning system) of our own design. This device consists of two servo motors mounted together such that one motor provides rotation about the vertical axis while the second motor provides rotation about an axis orthogonal to vertical. An important characteristic of the goniometer is that the rotational axes of the two motors intersect at a point at the center of the HiBall optical sphere; this point is defined as the origin of the HiBall. (It is this origin that provides the reference for the HiBall state during run time as described in section 5.3.) The rotational positioning motors were rated to provide 20 arc-second precision; we further calibrated them using a surveying grade theodolite, an angle measuring system, to 6 arc seconds. In order to determine the mapping between sensor image plane coordinates and three-space rays, we use a single LED mounted at a fixed location in the laboratory such that it is centered in the view directly out of the top lens of the HiBall. This ray defines the Z or up axis for the HiBall coordinate system. We sample other rays by rotating the goniometer motors under computer control. We sample each view with rays spaced about every 6 minutes of arc throughout the field of view. We repeat each measurement 100 times in order to reduce the effects of noise on the individual measurements and to estimate the standard deviation of the measurements. Given the tables of approximately 2500 measurements for each view, we first determine a 3 by 4 view matrix using standard linear least-squares techniques. Then we determine the deviation of

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	each measured point from that predicted by the ideal linear model. These deviations are re-sampled into a 25 by 25 grid indexed by sensor-plane coordinates using a simple scan conversion procedure and averaging. Given a measurement from a sensor at run time we convert it to an "ideal" measurement by subtracting a deviation bi-linearly interpolated from the nearest 4 entries in the table. Welch 1999 at 3 The HiBall tracker system (Figure 2) provides six-degree-of freedom tracking of devices in real time. An outward looking infrared-sensing subsystem called a HiBall (Figure 1, lower-right) is mechanically fixed to each device to be tracked. The HiBalls view an environment containing a subsystem of fixed-location infrared beacons which we call the Ceiling. At the present time, the beacons are in fact entirely located in the ceiling of our laboratory, but could as well be located in walls or other arbitrary fixed locations. These subsystems are coordinated by a Ceiling-HiBall Interface Board (CIB) which provides communication and synchronization functions between the host computer and the attached subsystems. Each HiBall has 26 narrow (less than 6 degree) views distributed over a large solid angle. Beacons are selectively flashed in a sequence such that they are seen by many different fields of view of each HiBall. Initial acquisition is performed using a brute force search through beacon space, but once initial lock is made, the selection of beacons to flash is tailored to the fields of view of the HiBalls. ***Tracking is maintained using a Kalman filter-based prediction-correction algorithm known as SCAAT***. This technique has been further extended to provide self-calibration of the Ceiling on-line with the tracking of the attached HiBalls. Welch 1999 at 2. 4.2 The HiBall As can be seen in Figure 1 and color plate image Welch 1 the HiBall is a hollow ball having dodecahedral symmetry with lenses in the upper six faces and lateral effect photo diodes (LEPDs) on the insides of the opposing six lower faces. This immediately gives six primary fields of view, or camera systems which share the same internal air space, and whose adjacent directions of view are uniformly separated by 57 degrees. While the original intent of the shared internal air space was to save space, we subsequently realized that light entering any lens sufficiently off axis can be seen by an adjacent LEPD. As such, five secondary fields of view are provided by the top or central lens, and three secondary fields of view are provided by the five other lenses. Overall, this provides 26 fields of view which are used to sense widely separated groups of beacons in the environment. While these extra views complicate the initialization of the Kalman filter as described in section 5.5, they turn out to be of great benefit during steady-state tracking by effectively increasing the overall HiBall field of view without sacrificing resolution. Welch 1999 at 2-3.

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CLAIM 1	HiBall
	4.3 The Ceiling-HiBall Interface Board The Ceiling-HiBalI Interface Board (CIB), shown below in Figure 4, provides communication and synchronization between a host personal computer, the Ceiling (section 4.1) and the HiBall (section 4.2). The CIB has four Ceiling ports allowing interleaving of ceiling panels for up to four simultaneous led flashes and/or higher Ceiling bandwidth for more simultaneous hiball usage. (The Ceiling bandwidth is inherently limited by LED current restrictions as described in section 4.1, but this can be increased by spatially multiplexing the Ceiling tiles.) The CIB has two tether interfaces that can communicate with up to four daisy-chained hiballs each. The full-duplex communication with the hiballs uses a modulation scheme (BPSK) allowing future wireless operation. The interface from the CIB to the host PC is the stable IEEE1284C extended parallel port (EPP) standard. The CIB comprises analog drive and receive components as well as digital logic components. The digital components implement store and forward in both directions and synchronize the timing of the LED "on" interval within the HiBall dark-light-dark intervals. The protocol supports fullduplex flow control. The data are arranged into packets containing error detection to insure data quality. Welch 1999 at 3. **The HiBall-3000 Optical Sensor** The HiBall-3000 tracker system is composed of two key integrated components; the HiBall Optical Sensor and the HiBall Ceiling Beacon Arrays. The HiBall Optical Sensor is composed of 6 lenses and photodiodes arranged so that each photodiode can 'view' infrared LEDs, in the Beacon Arrays mounted on the ceiling, through several of the 6 lenses. The assembly includes signal processing and analog-to-digital conversion circuitry. The total weight is about 6 ounces, making it light enough to comfortably mount on a headmounted display or hand-held device. By locating the sensors on the person or object being tracked — *inside-out tracking* — sensitivity around the working area is increased and the tracker area scales almost without limit. An entire lab, movie set, or assembly area can be tracked. The HiBall can also be mounted on a small probe or stylus, enabling extremely accurate measurements of individual objects within a large space. For example, this can be used for very rapid measurement of actual television or movie sets or other real-world objects to be combined with virtual scenes. No other device can provide comparable speed and accuracy over a wide area. 3rdTech at 1. **HiBall Beacon Array Modules** The infrared LEDs 'seen' by the HiBall Sensor are embedded in a series of ceiling mounted strips forming a 2D Beacon Array - 8 LEDs per strip; 6 strips per Beacon Array Module (BAM). These strips are designed to slip easily

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CLAIM 1	HiBall
	into a typical 'drop ceiling' with no changes required in panels, lights, vents, etc. - the more BAMs employed, the greater the range of the tracker. The arrays are highly modular — available in configurations covering as little as 64 square feet (8' x 8') or more than 1,600 square feet (40' x 40'). And no special adjustments are required to the ceiling structure — the system's precision is unaffected by typical variations in ceiling height. The HiBall Sensor and the Beacon Arrays are synchronized by a Ceiling- HiBall Interface Board (CIB), part of the system's integrated PC, which enables extremely high rates of LED 'sightings'— approximately 2,000 per second. This results in a tracker update rate of 2,000 Hz — several times faster than other commercially available wide-area trackers. Faster updates means lower latency and more accurate tracking - even with rapid movements. **AutoCalibration** The system makes use of a *single constraint at a time* (SCAAT) algorithm to compute the location and orientation of the HiBall Sensor at every LED sighting. In addition, the system incorporates *auto-calibration* — tuning the modeled location of individual LEDs on every update. This accommodates typical shifts and movements in the ceiling tiles and BAMs without loss of accuracy or performance. **Applications** The range and performance of the HiBall-3000 Tracker open up new possibilities for large-scale virtual reality such as exploring full-size architectural designs or engineering prototypes. Its precision enables largescale augmented reality for applications in medicine, training and entertainment where accurate correspondence between physical reality and the virtual world are critical. **Proven Results** Developed in the Computer Science Department of the University of North Carolina at Chapel Hill (see www.cs.unc.edu/~tracker), the original HiBall tracker has been in use since 1997 and has consistently exceeded performance expectations. 3rdTech at 1. **3. SYSTEM OVERVIEW** The HiBall Tracking System consists of three main components (Figure 6). An outward-looking sensing unit we call the *HiBall* is fixed to each user to be tracked. The HiBall unit observes a subsystem of fixed-location infrared LEDs we call the *Ceiling* 1. Communication and synchronization between the host computer and these subsystems is coordinated by the *Ceiling-HiBall Interface Board* (CIB). In Section 4 we describe these components in more detail. Each HiBall observes LEDs through multiple sensor-lens *views* that are distributed over a large solid angle. LEDs are sequentially flashed (one at a time) such that they are seen via a diverse set of views for each HiBall. Initial *acquisition* is performed using a brute force search through LED space, but once initial lock is made, the

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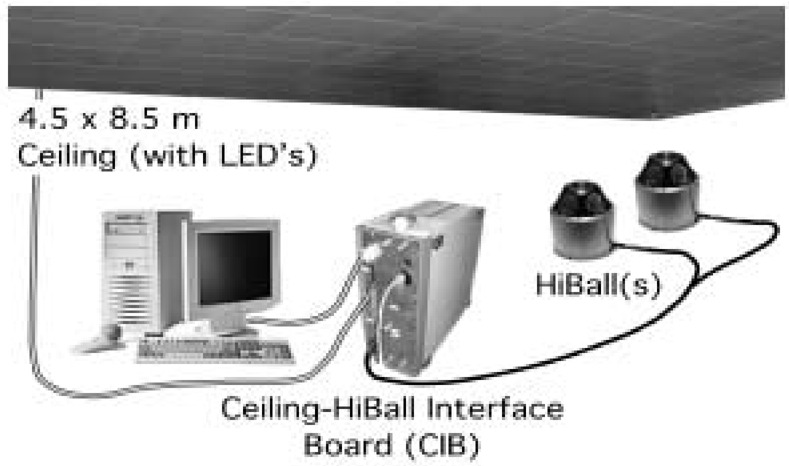
CLAIM 1	HiBall
	selection of LEDs to flash is tailored to the views of the active HiBall units. ***Pose estimates are maintained using a Kalman-filter-based prediction-correction approach known as single-constraint-at-a-time or SCAAT tracking. This technique has been extended to provide self-calibration of the Ceiling, concurrent with HiBall tracking***. In Section 5 we describe the methods we employ, including the initial acquisition process and the SCAAT approach to pose estimation, with the *autocalibration* extension. Welch HiBall at 6.  **Figure 6** Welch HiBall at Fig. 6. **4.3 The Ceiling-HiBall Interface Board** The Ceiling-HiBall Interface Board or CIB (Figure 11) provides communication and synchronization between a host personal computer, the HiBall (Section 4.1), and the Ceiling (Section 4.2). The CIB has four Ceiling ports allowing interleaving of ceiling panels for up to four simultaneous LED flashes and/or higher Ceiling bandwidth. (The Ceiling bandwidth is inherently limited by LED power restrictions as described in Section 4.2, but this can be increased by spatially multiplexing the Ceiling panels.) The CIB has two tether interfaces that can communicate with up to four daisy-chained HiBall units. The full-duplex communication with the HiBall units uses a modulation scheme (BPSK) allowing future wireless operation. The interface from the CIB to the host PC is the stable IEEE1284C extended parallel port (EPP) standard. The CIB comprises analog drive and receive

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CLAIM 1	HiBall
	components as well as digital logic components. The digital components implement store and forward in both directions and synchronize the timing of the LED "on" interval within the HiBall dark-light-dark intervals (Section 5.2). The protocol supports full-duplex flow control. The data are arranged into packets that incorporate error detection. Welch HiBall at 8-9. **4. SYSTEM COMPONENTS** **4.1 The HiBall** The original electro-optical tracker (Figure 3, bottom) used independently housed lateral effect photo-diode units (LEPDs) attached to a light-weight tubular framework. As it turns out, the mechanical framework would flex (distort) during use, contributing to estimation errors. In part to address this problem the HiBall sensor unit was designed as a single rigid hollow ball having dodecahedral symmetry, with lenses in the upper six faces and LEPD on the insides of the opposing six lower faces (Figure 7). This immediately gives six primary "camera" *views* uniformly spaced by 57 degrees. The views efficiently share the same internal air space, and are rigid with respect to each other. In addition, light entering any lens sufficiently off axis can be seen by a neighboring LEPD, giving rise to five secondary views through the top or central lens, and three secondary views through the five other lenses. Overall, this provides 26 fields of view which are used to sense widely separated groups of LEDs in the environment. While the extra views complicate the initialization of the Kalman filter as described in Section 5.5, they turn out to be of great benefit during steady-state tracking by effectively increasing the overall HiBall field of view without sacrificing optical sensor resolution. The lenses are simple plano-convex fixed-focus lenses. Infrared (IR) filtering is provided by fabricating the lenses themselves from RG-780 Schott glass filter material which is opaque to better than 0.001% for all visible wavelengths, and transmissive to better than 99% for IR wavelengths longer than 830 nm. The longwave filtering limit is provided by the DLS-4 LEPD silicon photodetector (UDT Sensors, Inc.) with peak responsivity at 950 nm but essentially blind above 1150 nm. The LEPDs themselves are not imaging devices; rather they detect the centroid of the luminous flux incident on the detector. The x-position of the centroid determines the ratio of two output currents, while the y-position determines the ratio of two other output currents. The total output current of each pair are commensurate, and proportional to the total incident flux. Consequently, focus is not an issue, so the simple fixed-focus lenses work well over a range of LED distances from about half a meter to infinity. The LEPDs and associated electronic components are mounted on a custom rigid-flex printed circuit board (Figure 8). This arrangement makes efficient

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CLAIM 1	HiBall
	use of the internal HiBall volume while maintaining isolation between analog and digital circuitry, and increasing reliability by alleviating the need for inter-component mechanical connectors. Figure 9 shows the physical arrangement of the folded electronics in the HiBall. Each LEPD has four transimpedance amplifiers (shown together as one "Amp" in Figure 9), the analog outputs of which are multiplexed with those of the other LEPDs, then sampled, held, and converted by four 16-bit Delta-Sigma analog-to-digital (A/D) converters. Multiple samples are integrated via an accumulator. The digitized LEPD data are organized into packets for communication back to the CIB. The packets also contain information to assist in error-detection. The communication protocol is simple, and while presently implemented by wire, the modulation scheme is amenable to a wireless implementation. The present wired implementation allows multiple HiBall units to be daisy-chained so a single cable can support a user with multiple HiBall units. Welch HiBall at 6-7. **1.3 The HiBall Tracking System** In this article we describe a new and vastly improved version of the 1991 system. We call the new system the *HiBall Tracking System*. Thanks to significant improvements in hardware and software this HiBall system offers unprecedented speed, resolution, accuracy, robustness, and flexibility. The bulky and heavy sensors and backpack of the previous system have been replaced by a small *HiBall* unit (Figure 4, bottom). In addition, the precisely machined LED ceiling panels of the previous system have been replaced by looser-tolerance panels that are relatively inexpensive to make and simple to install (Figure 4, top; Figure 10). Finally, we are using an unusual ***Kalman-filter-based algorithm that generates very accurate pose estimates at a high rate with low latency, and simultaneously self-calibrates the system***. As a result of these improvements the HiBall Tracking System can generate over 2000 pose estimates per second, with less than one millisecond of latency, better than 0.5 millimeters and 0.03 degrees of absolute error and noise, everywhere in a 4.5 by 8.5 meter room (with over two meters of height variation). The area can be expanded by adding more panels, or by using checkerboard configurations which spread panels over a larger area. The weight of the user-worn HiBall is about 300 grams, making it lighter than one optical sensor in the 1991 system. Multiple HiBall units can be daisy chained together for head or hand tracking, pose-aware input devices, or precise 3D point. Welch HiBall at 4.

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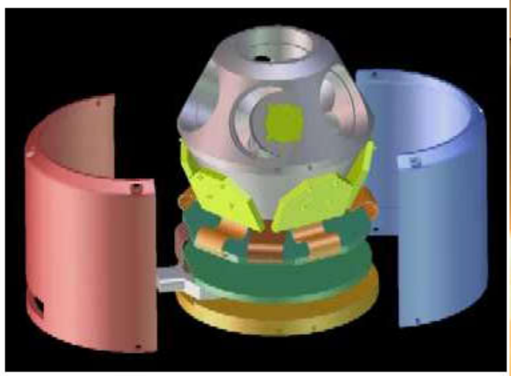
CLAIM 1	HiBall
	The HiBall tracking system resolves linear motion of less than 0.2mm and angular motions under 0.03 degrees without the distortion seen in magnetic trackers. The update rate is greater than 1500 Hz and latency is about 1ms. To our knowledge, this was the first and remains the only demonstrated scalable tracking system for HMDs. UNC HiBall Tracker at 1. **The HiBall** The HiBall is a cluster of 6 lenses and 6 photodiodes arranged so that each photodiodes can view LEDs through several of the 6 lenses, providing 26 view frustra originating at the HiBall. The assembly will include signal processing and A/D conversion circuitry. The total weight is about 5 ounces, making it lighter than just one of the cameras in the previous generation ceiling tracker. The HiBall and the ceiling panel are synchronized by a custom interface board which allows very high rate of LED sightings. The hardware alone can perform more than 3,000 sightings per second, while the whole system tracks using about 1,500. UNC HiBall Tracker at 1. **The Hiball** (Shown without lenses)   UNC HiBall Tracker at 2. **The SCAAT algorithm**

Exhibit E-11

CLAIM 1	HiBall
	The UNC HiBall Tracker relies on the SCAAT (Single Constraint At A Time) algorithm to compute the user's position and orientation from the individual sightings the HiBall makes of LEDs on the ceiling panels. The algorithm makes innovative use of an Extended Kalman Filter to provide position and orientation updates after each individual LED sighting, rather than after a group of several sightings as in the previous generation of UNC ceiling tracker. In addition, SCAAT improves on previously developed auto calibration techniques to allow on-line calibration as described below. For more information see Greg Welch's SCAAT page which includes links to Greg Welch and Gary Bishop's 1997 SIGGRAPH paper on SCAAT. UNC HiBall Tracker at 2. **Autocalibration** The current ceiling's lower cost design was made possible by an auto calibration process described in Gottschalk93. The SCAAT algorithm improves on this by allowing auto calibration, tuning the actual LED positions, to be performed while the system is tracking. This accommodates shifts in the tiles and LEDs which can occur during normal use. In addition this technique opens possibilities for even less initial knowledge of LED placement than the current ceiling provides. As a test and demonstration of the autocalibration abilities of SCAAT, we have intentionally raised ceiling panels from their correct position. Here Dr. Gary Bishop is shown making the adjustments. The system was given only the initial flat LED positions, but after less than ten minutes of use (successfully tracking with the misplaced panels), SCAAT had accurately adjusted its knowledge of the LED positions through displacements more than 5cm. The above visualization shows the final measured LED positions. UNC HiBall Tracker at 2-3.

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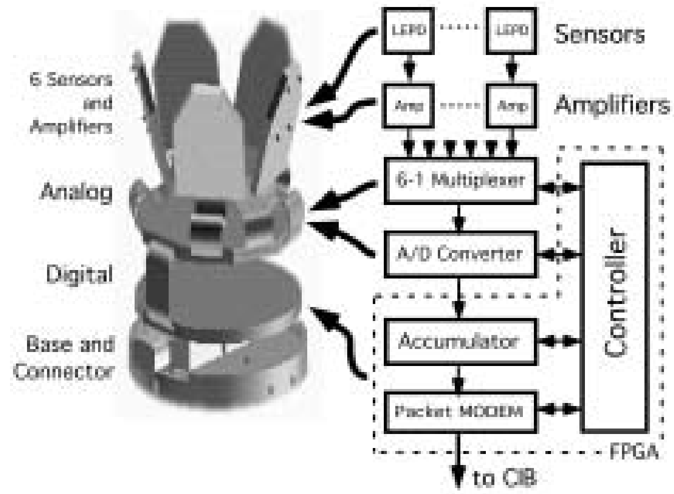
CLAIM 1	HiBall
	 **Figure 9** Welch HiBall at Fig. 9. **4.2 The Ceiling** As presently implemented, the infrared LEDs are packaged in 61 centimeter square *panels*, to fit a standard false ceiling grid (Figure 10, top). Each panel uses five printed circuit boards: a main controller board and four identical transverse-mounted *strips* (bottom). Each strip is populated with eight LEDs for a total of 32 LEDs per panel. We mount the assembly on top of a metal panel such that the LEDs protrude through 32 corresponding holes. The design results in a Ceiling with a rectangular LED pattern with periods of 7.6 and 15.2 centimeters. This spacing is used for the initial estimates of the LED positions in the lab, then during normal operation the SCAAT algorithm continually refines the LED position estimates (Section 5.4). The SCAAT *autocalibration* not only relaxes design and installation constraints, but provides greater precision in the face of initial and ongoing uncertainty in the Ceiling structure. We currently have enough panels to cover an area approximately 5.5 by 8.5 meters with a total of approximately 3,000 LEDs. 1 The panels are daisy-chained to each other, and panel selection encoding is position (rather than device) dependent. Operational commands are presented to the first panel of the daisy chain. At each panel, if the panel select code is zero the controller decodes and executes the operation; else it decrements the panel select code and passes it along to the next panel (controller). Upon decoding, a particular LED is selected and the LED is energized. The LED brightness (power) is selectable for *automatic gain control* as

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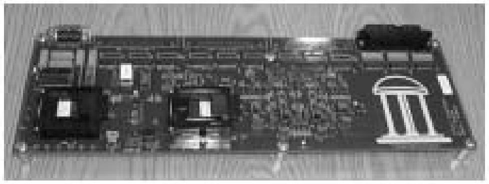
CLAIM 1	HiBall
	described in Section 5.2. We currently use Siemens SFH-487P GaAs LEDs which provide both a wide angle radiation pattern and high peak power, emitting at a center wavelength of 880 nm in the near IR. These devices can be pulsed up to 2.0 Amps for a maximum duration of 200 with a 1:50 (on:off) duty cycle. While the current Ceiling architecture allows flashing of only one LED at a time, LEDs may be flashed in any sequence. As such no single LED can be flashed too long or too frequently. We include both hardware and software protection to prevent this. **4.3 The Ceiling-HiBall Interface Board** The Ceiling-HiBall Interface Board or CIB (Figure 11) provides communication and synchronization between a host personal computer, the HiBall (Section 4.1), and the Ceiling (Section 4.2). The CIB has four Ceiling ports allowing interleaving of ceiling panels for up to four simultaneous LED flashes and/or higher Ceiling bandwidth. (The Ceiling bandwidth is inherently limited by LED power restrictions as described in Section 4.2, but this can be increased by spatially multiplexing the Ceiling panels.) The CIB has two tether interfaces that can communicate with up to four daisy-chained HiBall units. The full-duplex communication with the HiBall units uses a modulation scheme (BPSK) allowing future wireless operation. The interface from the CIB to the host PC is the stable IEEE1284C extended parallel port (EPP) standard. The CIB comprises analog drive and receive components as well as digital logic components. The digital components implement store and forward in both directions and synchronize the timing of the LED “on” interval within the HiBall dark-light-dark intervals (Section 5.2). The protocol supports full-duplex flow control. The data are arranged into packets that incorporate error detection. Welch HiBall at 8-9.  Figure 11 Welch HiBall at Fig. 11. **The SCAAT algorithm**

CLAIM 1	HiBall
	The UNC HiBall Tracker relies on the SCAAT (Single Constraint At A Time) algorithm to compute the user's position and orientation from the individual sightings the HiBall makes of LEDs on the ceiling panels. The algorithm makes innovative use of an Extended Kalman Filter to provide position and orientation updates after each individual LED sighting, rather than after a group of several sightings as in the previous generation of UNC ceiling tracker. In addition, SCAAT improves on previously developed auto calibration techniques to allow on-line calibration as described below. For more information see Greg Welch's SCAAT page which includes links to Greg Welch and Gary Bishop's 1997 SIGGRAPH paper on SCAAT. UNC HiBall Tracker at 2. **Autocalibration** The current ceiling's lower cost design was made possible by an auto calibration process described in Gottschalk93. The SCAAT algorithm improves on this by allowing auto calibration, tuning the actual LED positions, to be performed while the system is tracking. This accommodates shifts in the tiles and LEDs which can occur during normal use. In addition this technique opens possibilities for even less initial knowledge of LED placement than the current ceiling provides. As a test and demonstration of the autocalibration abilities of SCAAT, we have intentionally raised ceiling panels from their correct position. Here Dr. Gary Bishop is shown making the adjustments. The system was given only the initial flat LED positions, but after less than ten minutes of use (successfully tracking with the misplaced panels), SCAAT had accurately adjusted its knowledge of the LED positions through displacements more than 5cm. The above visualization shows the final measured LED positions. UNC HiBall Tracker at 2-3. **6.2.2 Complete System Simulations.** To produce realistic data for developing and tuning our algorithms we collected several motion paths *(*sequences of pose estimates) from our first generation electro-optical tracker (Figure 3) at its 70 Hz maximum report rate. These paths were recorded from both naive users visiting our monthly "demo days" and from experienced users in our labs. In the same fashion as we had done for (Azuma & Bishop, 1994a) we filtered the raw path data with a non-causal zero-phase-shift low-pass filter to eliminate energy above 2 Hz. The output of the low-pass filtering was then re-sampled at whatever rate we wanted to run the simulated tracker, usually 1000 Hz. For the purposes of our simulations we considered these resampled paths to be the "truth"—a perfect representation of a user's motion. Tracking error was determined by comparing the "true" path to the estimated path produced by the tracker. The simulator reads camera models describing the 26 views, the sensor noise parameters, the LED positions and their expected error, and the motion path described above. Before beginning the simulation, the LED

CLAIM 1	HiBall
	positions are perturbed from their ideal positions by adding normally distributed error to each axis. Then, for each simulated cycle of operation, the "true" pose are updated using the input motion path. Next, a view is chosen and a visible LED within that view is selected, and the image-plane coordinates of the LED on the chosen sensor are computed using the camera model for the view and the LED as described in Section 5.3. These sensor coordinates are then perturbed based on the sensor noise model (Section 6.2.1) using the distance and angle to the LED. Now these noise corrupted sensor readings are fed to the SCAAT filter to produce an updated position estimate. The position estimate is compared to the true position to produce a scalar error metric described next. Welch HiBall at 16-17. **5.4 On-line LED Autocalibration** Along with the benefit of simplicity and speed, the SCAAT approach offers the additional capability of being able to estimate the 3D positions of the LEDs in the world concurrently with the pose of the HiBall, on line, in real time. This capability is a tremendous benefit in terms of the accuracy and noise characteristics of the estimates. Accurate LED position estimates are so important that prior to the introduction of the SCAAT approach a specialized off-line approach was developed to address the problem (Gottschalk & Hughes, 1993). The method we now use for autocalibration involves defining a distinct SCAAT Kalman filter for each LED. Specifically, for each LED we maintain a state $\bar{l}$ (estimate of the 3D position) and a 3x3 Kalman filter covariance. At the beginning of each estimation cycle we form an augmented state vector $\hat{x}$ using the appropriate LED state and the current HiBall state: $\hat{x} = [\bar{x}^T, \bar{l}^T]^T$. Similarly we augment the Kalman filter error covariance matrix with that of the LED filter. We then follow the normal steps outlined in Section 5.3, with the result being that the LED portion of the filter state and covariance is updated in accordance with the measurement residual. At the end of the cycle we extract the LED portions of the state and covariance from the augmented filter, and save them externally. The effect is that as the system is being used, it continually refines its estimates of the LED positions, thereby continually improving its estimates of the HiBall pose. Again, for additional information see (Welch, 1996; Welch & Bishop, 1997). Welch HiBall at 13. The Kalman filter requires both a model of the process dynamics, and a model of the relationship between the process state and the available measurements. In part due to the simplicity of the SCAAT approach we are able to use a simple PV (position-velocity) process model (Brown & Hwang, 1992). Consider the simple example state vector $\bar{x}(t) = [x_p(t), x_v(t)]^T$ where the first element $x_p(t)$ is the pose (position or orientation) and the second

CLAIM 1	HiBall
	element $x_v(t)$ is the corresponding velocity, i.e. $x_v(t) = \frac{d}{dt}x_p(t)$. We model the continuous change in the HiBall state with the simple differential equation $\frac{d}{dt}\bar{x}(t) = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x_p(t) \\ x_v(t) \end{bmatrix} + \begin{bmatrix} 0 \\ \mu \end{bmatrix} u(t), \quad (1)$ where *u(t)* is a normally-distributed white (in the frequency spectrum) scalar noise process, and the scalar μ represents the magnitude or *spectral density* of the noise. We use a similar model with a distinct noise process for each of the six pose elements. We determine the individual noise magnitudes using an off-line simulation of the system and a non-linear optimization strategy that seeks to minimize the variance between the estimated pose and a known motion path. (See Section 6.2.2.) The differential equation (1) represents a continuous integrated random walk, or an integrated *Wiener* or *Brownian-motion* process. Specifically, we model each component of the linear and angular HiBall velocities as a random walk, and then use these (assuming constant inter-measurement velocity) to estimate the HiBall pose at time $t + \delta t$ as follows: $\bar{x}(t + \delta t) = \begin{bmatrix} 1 & \delta t \\ 0 & 1 \end{bmatrix} \bar{x}(t) \quad (2)$ for each of the six pose elements. In addition to a relatively simple process model, the HiBall measurement model is relatively simple. For any Ceiling LED (Section 4.2) and HiBall view (Section 4.1), the 2D sensor measurement can be modeled as $\begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} c_x / c_z \\ c_y / c_z \end{bmatrix} \quad (3)$ where $\begin{bmatrix} c_x \\ c_y \\ c_z \end{bmatrix} = VR^{T}(\bar{l}_{xyz} - \bar{x}_{xyz}), \quad (4)$ is the camera viewing matrix from Section 5.1, is the position of the LED in the world, is the position of the HiBall in the world, and is a rotation matrix corresponding to the orientation of the HiBall in the world. In practice we maintain the orientation of the HiBall as a combination of a global (external to the state) quaternion and a set of incremental angles as described in (Welch, 1996; Welch & Bishop, 1997).

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CLAIM 1	HiBall
	Welch HiBall at 11-12. **5.2 On-Line HiBall Measurements** Upon receiving a command from the CIB (Section 4.3), which is synchronized with a CIB command to the ceiling, the HiBall selects the specified LEPD and performs three measurements, one before the LED flashes, one during the LED flash, and one after the LED flash. Known as "dark-light-dark", this technique is used to subtract out DC bias, low frequency noise, and background light from the LED signal. We then convert the measured sensor coordinates to "ideal" coordinates using the calibration tables described in Section 5.1. In addition, during run time we attempt to maximize the signal-to-noise ratio of the measurement with an automatic gain control scheme. For each LED we store a target signal strength factor. We compute the LED current and number of integrations (of successive accumulated A/D samples) by dividing this strength factor by the square of the distance to the LED, estimated from the current position estimate. After a reading we look at the strength of the actual measurement. If it is larger than expected we reduce the gain, if it is less than expected we increase the gain. The increase and decrease are implemented as on-line averages with scaling such that the gain factor decreases rapidly (to avoid overflow) and increases slowly. Finally we use the measured signal strength to estimate the noise on the signal using (Chi, 1995), and then use this as the measurement noise estimate for the Kalman filter (Section 5.3). Welch HiBall at 9-10. *See also* hiball/src/libs/tracker and /cib, including but not limited to the following: /hiball/src/libs/tracker/hiballfilter.h /hiball/src/libs/tracker/hiballfilter.cpp *See also* Defendants' Invalidity Contentions for further discussion.

B. Dependent Claim 2

Claim 2	HiBall
[2] The system of claim 1 wherein the sensor subsystem includes one or more sensor modules, each providing an interface for interacting with a corresponding set of one or more sensing elements.	At least under Plaintiffs' apparent infringement theory, HiBall discloses, either expressly or inherently, the system of claim 1 wherein the sensor subsystem includes one or more sensor modules, each providing an interface for interacting with a corresponding set of one or more sensing elements. In the alternative, this element would be obvious over HiBall in light of the other references disclosed in Defendants' Invalidity Contentions and/or the knowledge of one of ordinary skill in the art. *See, e.g.*: As a result of these improvements the HiBall Tracker can generate over 2000 estimates per second, with less than one millisecond of latency. The system exhibits sub-millimeter translation noise and similar measured accuracy, as well as less than 0.03 degrees of orientation noise with similar measured accuracy. The weight of the user-worn HiBall is about 300 grams, making it lighter than just one camera in the 1991 system. The working volume of the current system is greater than 90 cubic meters (greater than 45 square meters of floor space, greater than 2 meters of height variation). This area can be expanded by adding more tiles, or by using checkerboard configurations which spread tiles over a larger area. Welch 1999 at 2. Both parts of the camera model are determined using a calibration procedure that relies on a goniometer (an angular positioning system) of our own design. This device consists of two servo motors mounted together such that one motor provides rotation about the vertical axis while the second motor provides rotation about an axis orthogonal to vertical. An important characteristic of the goniometer is that the rotational axes of the two motors intersect at a point at the center of the HiBall optical sphere; this point is defined as the origin of the HiBall. (It is this origin that provides the reference for the HiBall state during run time as described in section 5.3.) The rotational positioning motors were rated to provide 20 arc-second precision; we further calibrated them using a surveying grade theodolite, an angle measuring system, to 6 arc seconds. In order to determine the mapping between sensor image plane coordinates and three-space rays, we use a single LED mounted at a fixed location in the laboratory such that it is centered in the view directly out of the top lens of the HiBall. This ray defines the Z or up axis for the HiBall coordinate system. We sample other rays by rotating the goniometer motors under computer control. We sample each view with rays spaced about every 6 minutes of arc throughout the field of view. We repeat each measurement 100 times in order to reduce the effects of noise on the individual measurements and to estimate the standard

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CLAIM 2	HiBall
	deviation of the measurements. Given the tables of approximately 2500 measurements for each view, we first determine a 3 by 4 view matrix using standard linear least-squares techniques. Then we determine the deviation of each measured point from that predicted by the ideal linear model. These deviations are re-sampled into a 25 by 25 grid indexed by sensor-plane coordinates using a simple scan conversion procedure and averaging. Given a measurement from a sensor at run time we convert it to an "ideal" measurement by subtracting a deviation bi-linearly interpolated from the nearest 4 entries in the table. Welch 1999 at 3 The HiBall tracker system (Figure 2) provides six-degree-of freedom tracking of devices in real time. An outward looking infrared-sensing subsystem called a HiBall (Figure 1, lower-right) is mechanically fixed to each device to be tracked. The HiBalls view an environment containing a subsystem of fixed-location infrared beacons which we call the Ceiling. At the present time, the beacons are in fact entirely located in the ceiling of our laboratory, but could as well be located in walls or other arbitrary fixed locations. ***These subsystems are coordinated by a Ceiling-HiBall Interface Board (CIB) which provides communication and synchronization functions between the host computer and the attached subsystems***. Each HiBall has 26 narrow (less than 6 degree) views distributed over a large solid angle. Beacons are selectively flashed in a sequence such that they are seen by many different fields of view of each HiBall. Initial acquisition is performed using a brute force search through beacon space, but once initial lock is made, the selection of beacons to flash is tailored to the fields of view of the HiBalls. Tracking is maintained using a Kalman filter-based prediction-correction algorithm known as SCAAT. This technique has been further extended to provide self-calibration of the Ceiling on-line with the tracking of the attached HiBalls. Welch 1999 at 2. 4.2 The HiBall As can be seen in Figure 1 and color plate image Welch 1 the HiBall is a hollow ball having dodecahedral symmetry with lenses in the upper six faces and lateral effect photo diodes (LEPDs) on the insides of the opposing six lower faces. This immediately gives six primary fields of view, or camera systems which share the same internal air space, and whose adjacent directions of view are uniformly separated by 57 degrees. While the original intent of the shared internal air space was to save space, we subsequently realized that light entering any lens sufficiently off axis can be seen by an adjacent LEPD. As such, five secondary fields of view are provided by the top or central lens, and three secondary fields of view are provided by the five other lenses. Overall, this provides 26 fields of view which are used to sense widely separated groups of beacons in the environment. While these extra views complicate the initialization of the Kalman filter as described in section 5.5, they turn out to be of great benefit during steady-state tracking by effectively increasing the overall HiBall field of view without sacrificing resolution.

CLAIM 2	HiBall
	Welch 1999 at 2-3. 4.3 The Ceiling-HiBall Interface Board The Ceiling-HiBalI Interface Board (CIB), shown below in Figure 4, provides communication and synchronization between a host personal computer, the Ceiling (section 4.1) and the HiBall (section 4.2). The CIB has four Ceiling ports allowing interleaving of ceiling panels for up to four simultaneous led flashes and/or higher Ceiling bandwidth for more simultaneous hiball usage. (The Ceiling bandwidth is inherently limited by LED current restrictions as described in section 4.1, but this can be increased by spatially multiplexing the Ceiling tiles.) ***The CIB has two tether interfaces that can communicate with up to four daisy-chained hiballs each. The full-duplex communication with the hiballs uses a modulation scheme (BPSK) allowing future wireless operation. The interface from the CIB to the host PC is the stable IEEE1284C extended parallel port (EPP) standard.*** The CIB comprises analog drive and receive components as well as digital logic components. The digital components implement store and forward in both directions and synchronize the timing of the LED "on" interval within the HiBall dark-light-dark intervals. The protocol supports fullduplex flow control. The data are arranged into packets containing error detection to insure data quality. Welch 1999 at 3. As part of an ongoing effort to develop a system that avoids such tradeoffs, the Tracker Research Group at the University of North Carolina (http:/ /www.cs.unc.edu/-tracker) has created a wide-area optoelectronic tracking technology that lets users move freely through full-scale virtual worlds in real time. Such a capability not only enables VR applications that would otherwise be difficult or impossible to achieve-such as the exploration of life-size architectural designs and room-filling molecular models-but it is also expected to be of value to augmented reality (AR). In AR, real and digital worlds are superimposed into one scene through the use of see-through head-mounted displays that rely either on mirrors to represent the physical world or video input. Highly accurate motion tracking is crucial because even small tracking errors can result in unacceptable misregistration between real and virtual objects. Called the HiBall Tracking System, the new technology is able to meet the needs of such applications through its implementation of four unique components: ceiling panels that house LED targets, a miniature optical- sensor cluster (the HiBall) that senses and digitizes the LED flashes, ***a custom interface board that facilitates communications among the various components of the system, and tracking software that processes the communications in real time.***

Exhibit E-11

CLAIM 2	HiBall
	On the Right Track at 2. **Inside-Out Tracking** Unlike traditional optical tracking methods, in which targets are attached to the object or person to be tracked and sensed by a camera in the environment, the HiBall system employs an "inside-out" approach, in which the sensors are user mounted and the LED targets are fixed in the environment. This distinction is important, says UNC research assistant professor Greg Welch, because it ensures constant sensitivity to orientation over the working area. Also, because the targets are in the ceiling tiles, the tracking environment is infinitely scalable by increasing the number of tiles. The HiBall itself is unique in that it does not rely on the same charged-couple devices (CCDs) that most digital cameras employ. Rather, it uses lateral-effect photo diodes (LEPDs). Unlike CCD's, LEPDs are not imaging devices. They are 2D optical sensors that produce four analog voltages, which together indicate the 2D position of the center of the light hitting the sensor. "There is no image to capture and interpret, simply four voltages to digitize, which is done right inside the HiBall;' says Welch. The control center of the tracking system is the Ceiling-HiBall Interface Board (CIB), which sends LED addresses and control signals to the ceiling to direct the flashing of the LEDs. It also communicates with the HiBall, sending control signals and receiving the digitized LEPD values. The PC tracking software sends requests to the CIB for a sample of a particular ceiling LED from a particular optical sensor. In response, the CIB tells the ceiling to flash the LED and tells the HiBall to sample the LEPD. The digitized LEPD data it receives is sent back to the PC. The system's tracking code relies on an estimation approach called SCAAT (single constraint at a time) tracking, which turns the individual LED sightings into a complete position and orientation, or pose, estimate for the HiBall. With SCAAT, individual observations are reported as soon as they're acquired, rather than at the end of a complete collection of measurements, providing some information about the user's pose. Subsequent measurements build on previous ones to improve the estimates. A filtering technique fuses a continuous sequence of these incomplete, single LED sightings into an ongoing sequence of complete estimates. To enhance the quality of the estimates and ensure low latency, thousands of LED sightings are generated per second. An autocalibration process compensates for shifts in the tiles and for inherent estimate inaccuracies. On the agenda for the HiBall system is the development of a wireless capability between the HiBall and the CIB. The researchers are also investigating more flexible LED strategies, including LED strips that can be hung from ceilings wherever needed. The group's long-term objective is to develop hybrid tracking approaches that will reduce the system's infrastructure to allow users to move beyond the lab, eventually outdoors, while maintaining system performance. In the meantime, the existing HiBall technology is headed toward commercialization by a new company called HiBall Tracker Inc., which is currently negotiating a technology license with UNC Chapel Hill.

Exhibit E-11

CLAIM 2	HiBall
	On the Right Track at 2. **The HiBall-3000 Optical Sensor** The HiBall-3000 tracker system is composed of two key integrated components; the HiBall Optical Sensor and the HiBall Ceiling Beacon Arrays. The HiBall Optical Sensor is composed of 6 lenses and photodiodes arranged so that each photodiode can 'view' infrared LEDs, in the Beacon Arrays mounted on the ceiling, through several of the 6 lenses. The assembly includes signal processing and analog-to-digital conversion circuitry. The total weight is about 6 ounces, making it light enough to comfortably mount on a headmounted display or hand-held device. By locating the sensors on the person or object being tracked — *inside-out tracking* — sensitivity around the working area is increased and the tracker area scales almost without limit. An entire lab, movie set, or assembly area can be tracked. The HiBall can also be mounted on a small probe or stylus, enabling extremely accurate measurements of individual objects within a large space. For example, this can be used for very rapid measurement of actual television or movie sets or other real-world objects to be combined with virtual scenes. No other device can provide comparable speed and accuracy over a wide area. 3rdTech at 1. **HiBall Beacon Array Modules** The infrared LEDs 'seen' by the HiBall Sensor are embedded in a series of ceiling mounted strips forming a 2D Beacon Array - 8 LEDs per strip; 6 strips per Beacon Array Module (BAM). These strips are designed to slip easily into a typical 'drop ceiling' with no changes required in panels, lights, vents, etc. - the more BAMs employed, the greater the range of the tracker. The arrays are highly modular — available in configurations covering as little as 64 square feet (8' x 8') or more than 1,600 square feet (40' x 40'). And no special adjustments are required to the ceiling structure — the system's precision is unaffected by typical variations in ceiling height. The HiBall Sensor and the Beacon Arrays are synchronized by a Ceiling- HiBall Interface Board (CIB), part of the system's integrated PC, which enables extremely high rates of LED 'sightings'— approximately 2,000 per second. This results in a tracker update rate of 2,000 Hz — several times faster than other commercially available wide-area trackers. Faster updates means lower latency and more accurate tracking - even with rapid movements. **AutoCalibration** The system makes use of a *single constraint at a time* (SCAAT) algorithm to compute the location and orientation of the HiBall Sensor at every LED sighting. In addition, the system incorporates *auto-calibration* — tuning the modeled location of individual LEDs on every update. This accommodates typical shifts and movements in the ceiling tiles and BAMs without loss of accuracy or performance.

Exhibit E-11

CLAIM 2	HiBall
	Applications The range and performance of the HiBall-3000 Tracker open up new possibilities for large-scale virtual reality such as exploring full-size architectural designs or engineering prototypes. Its precision enables largescale augmented reality for applications in medicine, training and entertainment where accurate correspondence between physical reality and the virtual world are critical. **Proven Results** Developed in the Computer Science Department of the University of North Carolina at Chapel Hill (see www.cs.unc.edu/~tracker), the original HiBall tracker has been in use since 1997 and has consistently exceeded performance expectations. 3rdTech at 1.

HiBall-3000 Specifications and Performance

Hardware Components	
HiBall Optical Sensor(s)	2 7/8" tall, 2 1/8" diam, 6 OZ
Beacon Array Module (BAM)	Six 2' x 1" x 7/8" strips, 8 sq. ft.
PC-based Controller	Includes CIB I/F Board
Connections	Ethernet (VRPN), Serial (Standard Library Interface)
Software Components	
VR Peripheral Network (VRPN) support	Integrate system with other VR devices
Standard Library Interface	Compatible with existing systems
HBT Toolkit	Tools for set up, configuration and testing
HBT Library	Low-level system access
Output	Stream or point mode; XYZ coordinates; Quaternion, Euler angles or rotation matrices

3rdTech at 2.

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CLAIM 2	HiBall
	HiBall-3000 Wide-Area Tracker Features • Very Wide Area — Scalable to over 1,600 sq.ft. • High Precision — Ideal for augmented reality apps and rapid scene digitizing • High-update, low latency — Solid, high-speed tracking; no "swimming" • Small, light sensor — Head or stylus mountable • Easy installation — Installs in standard drop-ceilings; requires no room modifications • Multiple sensors — Multiple participants or head plus hand tracking • No metal/sound interference — Requires no modification of the environment • Accurate every-where — Consistent tracking near edges of space as well as in center 3rdTech at 2. **3. SYSTEM OVERVIEW** The HiBall Tracking System consists of three main components (Figure 6). An outward-looking sensing unit we call the *HiBall* is fixed to each user to be tracked. The HiBall unit observes a subsystem of fixed-location infrared LEDs we call the *Ceiling* 1. Communication and synchronization between the host computer and these subsystems is coordinated by the *Ceiling-HiBall Interface Board* (CIB). In Section 4 we describe these components in more detail. Each HiBall observes LEDs through multiple sensor-lens *views* that are distributed over a large solid angle. LEDs are sequentially flashed (one at a time) such that they are seen via a diverse set of views for each HiBall. Initial *acquisition* is performed using a brute force search through LED space, but once initial lock is made, the selection of LEDs to flash is tailored to the views of the active HiBall units. Pose estimates are maintained using a Kalman-filter-based prediction-correction approach known as *single-constraint-at-a-time* or SCAAT tracking. This technique has been extended to provide self-calibration of the Ceiling, concurrent with HiBall tracking. In Section 5 we describe the methods we employ, including the initial acquisition process and the SCAAT approach to pose estimation, with the *autocalibration* extension. Welch HiBall at 6.

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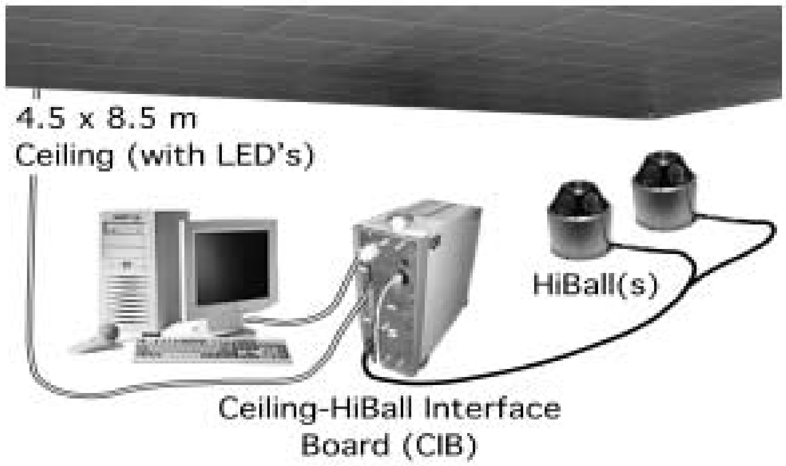
CLAIM 2	HiBall
	 **Figure 6** Welch HiBall at Fig. 6. **4.3 The Ceiling-HiBall Interface Board** The Ceiling-HiBall Interface Board or CIB (Figure 11) provides communication and synchronization between a host personal computer, the HiBall (Section 4.1), and the Ceiling (Section 4.2). The CIB has four Ceiling ports allowing interleaving of ceiling panels for up to four simultaneous LED flashes and/or higher Ceiling bandwidth. (The Ceiling bandwidth is inherently limited by LED power restrictions as described in Section 4.2, but this can be increased by spatially multiplexing the Ceiling panels.) The CIB has two tether interfaces that can communicate with up to four daisy-chained HiBall units. The full-duplex communication with the HiBall units uses a modulation scheme (BPSK) allowing future wireless operation. The interface from the CIB to the host PC is the stable IEEE1284C extended parallel port (EPP) standard. The CIB comprises analog drive and receive components as well as digital logic components. The digital components implement store and forward in both directions and synchronize the timing of the LED "on" interval within the HiBall dark-light-dark intervals (Section 5.2). The protocol supports full-duplex flow control. The data are arranged into packets that incorporate error detection. Welch HiBall at 8-9.

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CLAIM 2	HiBall
	4. SYSTEM COMPONENTS **4.1 The HiBall** The original electro-optical tracker (Figure 3, bottom) used independently housed lateral effect photo-diode units (LEPDs) attached to a light-weight tubular framework. As it turns out, the mechanical framework would flex (distort) during use, contributing to estimation errors. In part to address this problem the HiBall sensor unit was designed as a single rigid hollow ball having dodecahedral symmetry, with lenses in the upper six faces and LEPD on the insides of the opposing six lower faces (Figure 7). This immediately gives six primary "camera" *views* uniformly spaced by 57 degrees. The views efficiently share the same internal air space, and are rigid with respect to each other. In addition, light entering any lens sufficiently off axis can be seen by a neighboring LEPD, giving rise to five secondary views through the top or central lens, and three secondary views through the five other lenses. Overall, this provides 26 fields of view which are used to sense widely separated groups of LEDs in the environment. While the extra views complicate the initialization of the Kalman filter as described in Section 5.5, they turn out to be of great benefit during steady-state tracking by effectively increasing the overall HiBall field of view without sacrificing optical sensor resolution. The lenses are simple plano-convex fixed-focus lenses. Infrared (IR) filtering is provided by fabricating the lenses themselves from RG-780 Schott glass filter material which is opaque to better than 0.001% for all visible wavelengths, and transmissive to better than 99% for IR wavelengths longer than 830 nm. The longwave filtering limit is provided by the DLS-4 LEPD silicon photodetector (UDT Sensors, Inc.) with peak responsivity at 950 nm but essentially blind above 1150 nm. The LEPDs themselves are not imaging devices; rather they detect the centroid of the luminous flux incident on the detector. The x-position of the centroid determines the ratio of two output currents, while the y-position determines the ratio of two other output currents. The total output current of each pair are commensurate, and proportional to the total incident flux. Consequently, focus is not an issue, so the simple fixed-focus lenses work well over a range of LED distances from about half a meter to infinity. The LEPDs and associated electronic components are mounted on a custom rigid-flex printed circuit board (Figure 8). This arrangement makes efficient use of the internal HiBall volume while maintaining isolation between analog and digital circuitry, and increasing reliability by alleviating the need for inter-component mechanical connectors. Figure 9 shows the physical arrangement of the folded electronics in the HiBall. Each LEPD has four transimpedance amplifiers (shown together as one "Amp" in Figure 9), the analog outputs of which are multiplexed with those of the other LEPDs, then sampled, held, and converted by four 16-bit Delta-Sigma

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CLAIM 2	HiBall
	analog-to-digital (A/D) converters. Multiple samples are integrated via an accumulator. The digitized LEPD data are organized into packets for communication back to the CIB. The packets also contain information to assist in error-detection. The communication protocol is simple, and while presently implemented by wire, the modulation scheme is amenable to a wireless implementation. The present wired implementation allows multiple HiBall units to be daisy-chained so a single cable can support a user with multiple HiBall units. Welch HiBall at 6-7. **1.3 The HiBall Tracking System** In this article we describe a new and vastly improved version of the 1991 system. We call the new system the *HiBall Tracking System*. Thanks to significant improvements in hardware and software this HiBall system offers unprecedented speed, resolution, accuracy, robustness, and flexibility. The bulky and heavy sensors and backpack of the previous system have been replaced by a small *HiBall* unit (Figure 4, bottom). In addition, the precisely machined LED ceiling panels of the previous system have been replaced by looser-tolerance panels that are relatively inexpensive to make and simple to install (Figure 4, top; Figure 10). Finally, we are using an unusual Kalman-filter-based algorithm that generates very accurate pose estimates at a high rate with low latency, and simultaneously self-calibrates the system. As a result of these improvements the HiBall Tracking System can generate over 2000 pose estimates per second, with less than one millisecond of latency, better than 0.5 millimeters and 0.03 degrees of absolute error and noise, everywhere in a 4.5 by 8.5 meter room (with over two meters of height variation). The area can be expanded by adding more panels, or by using checkerboard configurations which spread panels over a larger area. The weight of the user-worn HiBall is about 300 grams, making it lighter than one optical sensor in the 1991 system. Multiple HiBall units can be daisy chained together for head or hand tracking, pose-aware input devices, or precise 3D point. Welch HiBall at 4. The HiBall tracking system resolves linear motion of less than 0.2mm and angular motions under 0.03 degrees without the distortion seen in magnetic trackers. The update rate is greater than 1500 Hz and latency is about 1ms. To our knowledge, this was the first and remains the only demonstrated scalable tracking system for HMDs. UNC HiBall Tracker at 1. **The HiBall**

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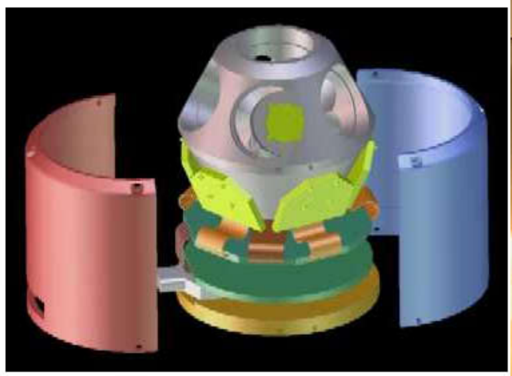
CLAIM 2	HiBall
	The HiBall is a cluster of 6 lenses and 6 photodiodes arranged so that each photodiodes can view LEDs through several of the 6 lenses, providing 26 view frustra originating at the HiBall. The assembly will include signal processing and A/D conversion circuitry. The total weight is about 5 ounces, making it lighter than just one of the cameras in the previous generation ceiling tracker. The HiBall and the ceiling panel are synchronized by a custom interface board which allows very high rate of LED sightings. The hardware alone can perform more than 3,000 sightings per second, while the whole system tracks using about 1,500. UNC HiBall Tracker at 1. **The Hiball** (Shown without lenses)   UNC HiBall Tracker at 2. **The SCAAT algorithm** The UNC HiBall Tracker relies on the SCAAT (Single Constraint At A Time) algorithm to compute the user's position and orientation from the individual sightings the HiBall makes of LEDs on the ceiling panels. The algorithm makes innovative use of an Extended Kalman Filter to provide position and orientation updates after each individual LED sighting, rather than after a group of several sightings as in the previous generation of UNC ceiling tracker. In addition, SCAAT improves on previously developed auto calibration techniques to allow on-line calibration as described below. For more information see Greg Welch's SCAAT page which includes links to

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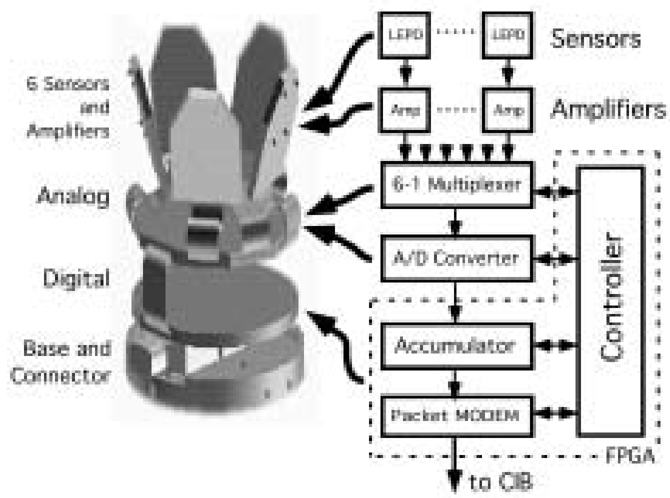
CLAIM 2	HiBall
	Greg Welch and Gary Bishop's 1997 SIGGRAPH paper on SCAAT. UNC HiBall Tracker at 2. **Autocalibration** The current ceiling's lower cost design was made possible by an auto calibration process described in Gottschalk93. The SCAAT algorithm improves on this by allowing auto calibration, tuning the actual LED positions, to be performed while the system is tracking. This accommodates shifts in the tiles and LEDs which can occur during normal use. In addition this technique opens possibilities for even less initial knowledge of LED placement than the current ceiling provides. As a test and demonstration of the autocalibration abilities of SCAAT, we have intentionally raised ceiling panels from their correct position. Here Dr. Gary Bishop is shown making the adjustments. The system was given only the initial flat LED positions, but after less than ten minutes of use (successfully tracking with the misplaced panels), SCAAT had accurately adjusted its knowledge of the LED positions through displacements more than 5cm. The above visualization shows the final measured LED positions. UNC HiBall Tracker at 2-3.  **Figure 9**

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CLAIM 2	HiBall
	Welch HiBall at Fig. 9. **4.2 The Ceiling** As presently implemented, the infrared LEDs are packaged in 61 centimeter square *panels*, to fit a standard false ceiling grid (Figure 10, top). Each panel uses five printed circuit boards: a main controller board and four identical transverse-mounted *strips* (bottom). Each strip is populated with eight LEDs for a total of 32 LEDs per panel. We mount the assembly on top of a metal panel such that the LEDs protrude through 32 corresponding holes. The design results in a Ceiling with a rectangular LED pattern with periods of 7.6 and 15.2 centimeters. This spacing is used for the initial estimates of the LED positions in the lab, then during normal operation the SCAAT algorithm continually refines the LED position estimates (Section 5.4). The SCAAT *autocalibration* not only relaxes design and installation constraints, but provides greater precision in the face of initial and ongoing uncertainty in the Ceiling structure. We currently have enough panels to cover an area approximately 5.5 by 8.5 meters with a total of approximately 3,000 LEDs. 1 The panels are daisy-chained to each other, and panel selection encoding is position (rather than device) dependent. Operational commands are presented to the first panel of the daisy chain. At each panel, if the panel select code is zero the controller decodes and executes the operation; else it decrements the panel select code and passes it along to the next panel (controller). Upon decoding, a particular LED is selected and the LED is energized. The LED brightness (power) is selectable for *automatic gain control* as described in Section 5.2. We currently use Siemens SFH-487P GaAs LEDs which provide both a wide angle radiation pattern and high peak power, emitting at a center wavelength of 880 nm in the near IR. These devices can be pulsed up to 2.0 Amps for a maximum duration of 200 with a 1:50 (on:off) duty cycle. While the current Ceiling architecture allows flashing of only one LED at a time, LEDs may be flashed in any sequence. As such no single LED can be flashed too long or too frequently. We include both hardware and software protection to prevent this. **4.3 The Ceiling-HiBall Interface Board** The Ceiling-HiBall Interface Board or CIB (Figure 11) provides communication and synchronization between a host personal computer, the HiBall (Section 4.1), and the Ceiling (Section 4.2). The CIB has four Ceiling ports allowing interleaving of ceiling panels for up to four simultaneous LED flashes and/or higher Ceiling bandwidth. (The Ceiling bandwidth is inherently limited by LED power restrictions as described in Section 4.2, but this can be increased by spatially multiplexing the Ceiling panels.) The CIB has two tether interfaces that can communicate with up to four daisy-chained HiBall units. The full-duplex communication with the HiBall units uses a modulation scheme (BPSK) allowing future wireless operation. The interface from the CIB to the host PC is the stable IEEE1284C extended parallel port (EPP) standard. The CIB comprises analog drive and receive

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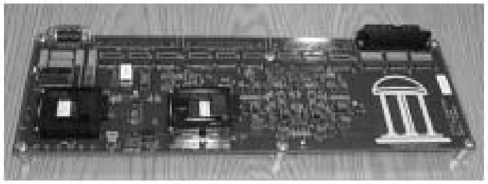
CLAIM 2	HiBall
	components as well as digital logic components. The digital components implement store and forward in both directions and synchronize the timing of the LED "on" interval within the HiBall dark-light-dark intervals (Section 5.2). The protocol supports full-duplex flow control. The data are arranged into packets that incorporate error detection. Welch HiBall at 8-9.  Figure 11 Welch HiBall at Fig. 11. **The SCAAT algorithm** The UNC HiBall Tracker relies on the SCAAT (Single Constraint At A Time) algorithm to compute the user's position and orientation from the individual sightings the HiBall makes of LEDs on the ceiling panels. The algorithm makes innovative use of an Extended Kalman Filter to provide position and orientation updates after each individual LED sighting, rather than after a group of several sightings as in the previous generation of UNC ceiling tracker. In addition, SCAAT improves on previously developed auto calibration techniques to allow on-line calibration as described below. For more information see Greg Welch's SCAAT page which includes links to Greg Welch and Gary Bishop's 1997 SIGGRAPH paper on SCAAT. UNC HiBall Tracker at 2. **Autocalibration** The current ceiling's lower cost design was made possible by an auto calibration process described in Gottschalk93. The SCAAT algorithm improves on this by allowing auto calibration, tuning the actual LED positions, to be performed while the system is tracking. This accommodates shifts in the tiles and LEDs which can occur during normal use. In addition this technique opens possibilities for even less initial knowledge of LED placement than the current ceiling provides.

CLAIM 2	HiBall
	As a test and demonstration of the autocalibration abilities of SCAAT, we have intentionally raised ceiling panels from their correct position. Here Dr. Gary Bishop is shown making the adjustments. The system was given only the initial flat LED positions, but after less than ten minutes of use (successfully tracking with the misplaced panels), SCAAT had accurately adjusted its knowledge of the LED positions through displacements more than 5cm. The above visualization shows the final measured LED positions. UNC HiBall Tracker at 2-3. **6.2.2 Complete System Simulations.** To produce realistic data for developing and tuning our algorithms we collected several motion paths *(*sequences of pose estimates) from our first generation electro-optical tracker (Figure 3) at its 70 Hz maximum report rate. These paths were recorded from both naive users visiting our monthly "demo days" and from experienced users in our labs. In the same fashion as we had done for (Azuma & Bishop, 1994a) we filtered the raw path data with a non-causal zero-phase-shift low-pass filter to eliminate energy above 2 Hz. The output of the low-pass filtering was then re-sampled at whatever rate we wanted to run the simulated tracker, usually 1000 Hz. For the purposes of our simulations we considered these resampled paths to be the "truth"—a perfect representation of a user's motion. Tracking error was determined by comparing the "true" path to the estimated path produced by the tracker. The simulator reads camera models describing the 26 views, the sensor noise parameters, the LED positions and their expected error, and the motion path described above. Before beginning the simulation, the LED positions are perturbed from their ideal positions by adding normally distributed error to each axis. Then, for each simulated cycle of operation, the "true" pose are updated using the input motion path. Next, a view is chosen and a visible LED within that view is selected, and the image-plane coordinates of the LED on the chosen sensor are computed using the camera model for the view and the LED as described in Section 5.3. These sensor coordinates are then perturbed based on the sensor noise model (Section 6.2.1) using the distance and angle to the LED. Now these noise corrupted sensor readings are fed to the SCAAT filter to produce an updated position estimate. The position estimate is compared to the true position to produce a scalar error metric described next. Welch HiBall at 16-17. **5.4 On-line LED Autocalibration** Along with the benefit of simplicity and speed, the SCAAT approach offers the additional capability of being able to estimate the 3D positions of the LEDs in the world concurrently with the pose of the HiBall, on line, in real time. This capability is a tremendous benefit in terms of the accuracy and noise characteristics of the estimates. Accurate LED position estimates are so important that prior to the introduction of the SCAAT approach a specialized off-line approach was developed to address the problem (Gottschalk & Hughes, 1993).

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CLAIM 2	HiBall
	The method we now use for autocalibration involves defining a distinct SCAAT Kalman filter for each LED. Specifically, for each LED we maintain a state $\bar{l}$ (estimate of the 3D position) and a 3x3 Kalman filter covariance. At the beginning of each estimation cycle we form an augmented state vector $\hat{x}$ using the appropriate LED state and the current HiBall state: $\hat{x} = [\bar{x}^T, \bar{l}^T]^T$. Similarly we augment the Kalman filter error covariance matrix with that of the LED filter. We then follow the normal steps outlined in Section 5.3, with the result being that the LED portion of the filter state and covariance is updated in accordance with the measurement residual. At the end of the cycle we extract the LED portions of the state and covariance from the augmented filter, and save them externally. The effect is that as the system is being used, it continually refines its estimates of the LED positions, thereby continually improving its estimates of the HiBall pose. Again, for additional information see (Welch, 1996; Welch & Bishop, 1997). Welch HiBall at 13. The Kalman filter requires both a model of the process dynamics, and a model of the relationship between the process state and the available measurements. In part due to the simplicity of the SCAAT approach we are able to use a simple PV (position-velocity) process model (Brown & Hwang, 1992). Consider the simple example state vector $\bar{x}(t) = [x_p(t), x_v(t)]^T$ where the first element $x_p(t)$ is the pose (position or orientation) and the second element $x_v(t)$ is the corresponding velocity, i.e. $x_v(t) = \frac{d}{dt}x_p(t)$. We model the continuous change in the HiBall state with the simple differential equation $$\frac{d}{dt}\bar{x}(t) = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x_p(t) \\ x_v(t) \end{bmatrix} + \begin{bmatrix} 0 \\ \mu \end{bmatrix} u(t), \quad (1)$$ where *u(t)* is a normally-distributed white (in the frequency spectrum) scalar noise process, and the scalar μ represents the magnitude or *spectral density* of the noise. We use a similar model with a distinct noise process for each of the six pose elements. We determine the individual noise magnitudes using an off-line simulation of the system and a non-linear optimization strategy that seeks to minimize the variance between the estimated pose and a known motion path. (See Section 6.2.2.) The differential equation (1) represents a continuous integrated random walk, or an integrated *Wiener* or *Brownian-motion* process. Specifically, we model each component of the linear and angular HiBall velocities as a random walk, and then use these (assuming constant inter-measurement velocity) to estimate the HiBall pose at time $t + \delta t$ as follows:

Exhibit E-11

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	$$\bar{x}(t+\delta t) = \begin{bmatrix} 1 & \delta t \\ 0 & 1 \end{bmatrix} \bar{x}(t) \qquad (2)$$ for each of the six pose elements. In addition to a relatively simple process model, the HiBall measurement model is relatively simple. For any Ceiling LED (Section 4.2) and HiBall view (Section 4.1), the 2D sensor measurement can be modeled as $$\begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} c_x/c_z \\ c_y/c_z \end{bmatrix} \qquad (3)$$ where $$\begin{bmatrix} c_x \\ c_y \\ c_z \end{bmatrix} = VR^{T}(\hat{l}_{xyz} - \bar{x}_{xyz}), \qquad (4)$$ is the camera viewing matrix from Section 5.1, is the position of the LED in the world, is the position of the HiBall in the world, and is a rotation matrix corresponding to the orientation of the HiBall in the world. In practice we maintain the orientation of the HiBall as a combination of a global (external to the state) quaternion and a set of incremental angles as described in (Welch, 1996; Welch & Bishop, 1997). Welch HiBall at 11-12. **5.2 On-Line HiBall Measurements** Upon receiving a command from the CIB (Section 4.3), which is synchronized with a CIB command to the ceiling, the HiBall selects the specified LEPD and performs three measurements, one before the LED flashes, one during the LED flash, and one after the LED flash. Known as "dark-light-dark", this technique is used to subtract out DC bias, low frequency noise, and background light from the LED signal. We then convert the measured sensor coordinates to "ideal" coordinates using the calibration tables described in Section 5.1. In addition, during run time we attempt to maximize the signal-to-noise ratio of the measurement with an automatic gain control scheme. For each LED we store a target signal strength factor. We compute the LED current and number of integrations (of successive accumulated A/D samples) by dividing this strength factor by the square of the distance to the LED, estimated from the current position estimate. After a reading we look at the strength of the actual measurement. If it is larger than expected we reduce the gain, if it is less than expected we increase the gain. The increase and decrease are implemented as on-line averages with scaling such that the gain

CLAIM 2	HiBall
	factor decreases rapidly (to avoid overflow) and increases slowly. Finally we use the measured signal strength to estimate the noise on the signal using (Chi, 1995), and then use this as the measurement noise estimate for the Kalman filter (Section 5.3). Welch HiBall at 9-10. *See also* hiball/src/libs/tracker and /cib, including but not limited to the following: "Tracker provides the UpdateState function which is repeatedly called to keep the hiball tracking. It goes through a cycle of choosing and [sic] LED to view, sighting that LED with the hardware, gauging if it was a successful result, passing successful results onto the Kalman Filter (HiballFilter), and reporting the latest state back in a TrackerState." /hiball/src/libs/tracker/tracker.h /hiball/src/libs/tracker/tracker.cpp The "ceiling" provides an interface for the set of LED "sensing elements". /hiball/src/libs/tracker/ceiling.h /hiball/src/libs/tracker/ceiling.h /hiball/src/libs/cib/hiball.h /hiball/src/libs/cib/hiball.cpp *See also* Defendants' Invalidity Contentions for further discussion.

C. Dependent Claim 3

Claim 3	HiBall
[3] The system of claim 2 wherein the interface enables the sensor module to perform computations independently of an implementation of the estimation subsystem.	At least under Plaintiffs' apparent infringement theory, HiBall discloses, either expressly or inherently, the system of claim 2 wherein the interface enables the sensor module to perform computations independently of an implementation of the estimation subsystem. In the alternative, this element would be obvious over HiBall in light of the other references disclosed in Defendants' Invalidity Contentions and/or the knowledge of one of ordinary skill in the art. See, e.g., In contrast, the approach we use with the new HiBall system produces tracker reports as each new measurement is made rather than waiting to form a complete collection of observations. Because single measurements under-constrain the mathematical solution, we refer to the approach as Single-Constraint-at-a-Time or SCAAT tracking [28, 291. The key is that the single measurements provide some information about the user's state, and thus can be used to incrementally improve a previous estimate. Using a Kalman filter [15] we intentionally fuse measurements that do not individually provide sufficient information, incorporating each individual measurement immediately as it is obtained. With this approach we are able to generate estimates more frequently, with less latency, with improved accuracy, and we are able to effectively estimate the LED positions on-line concurrently while tracking the HiBall (section 5.4). We use a Kalman filter, a minimum variance stochastic estimator, to estimate the HiBall state 5, i.e. the position and orientation of the HiBall. We use a Kalman filter in part because the sensor measurement noise and the typical user motion dynamics can be modeled as normally-distributed random processes, but also because we want an efficient online method of estimation. A basic introduction to the Kalman filter can be found in Chapter 1 of [17], while a more complete introductory discussion can be found in [20], which also contains some interesting historical narrative. More extensive references can be found in [7,12,14,16,17, 301. The Kalman filter has been used previously to address similar or related problems. See for example [2, 3,9, 10, 18, 231, and most recently [113. The SCAAT approach on the other hand is an attempt to reverse this cycle. Because we intentionally use a single constraint per estimate, the algorithmic complexity is drastically reduced, which reduces the execution time, and hence the amount of motion between estimation cycles. Because the amount of motion is limited we are able to use a simple dynamic (process) model in the Kalman filter, which further simplifies the computations. In short, the simplicity of the approach means it can run very fast, which means it can produce estimates very rapidly, with low

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CLAIM 3	HiBall
	noise. The Kalman filter requires both a model of the process dynamics, and a model of the relationship between the process state and the available measurements. In part due to the simplicity of the SCAAT approach we are able to use a very simple process model. We model the continuous change in the HiBall state vector Z(t) with the simple differential equation $$\frac{d}{dt}\bar{x}(t) = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \bar{x}_1(t) \\ \bar{x}_2(t) \end{bmatrix} + \begin{bmatrix} 0 \\ \mu \end{bmatrix} u(t),$$ where the scalar $$\bar{x}_2(t) = \frac{d}{dt}\bar{x}_1(t),$$ $u(t)$ is a normally-distributed scalar white noise process, and the scalar μ represents the magnitude of the noise (the spectral density). A similar model with a distinct noise magnitude μ is used for each of the six position and orientation elements. The individual noise magnitudes are determined using an off-line simulation of the system and a non-linear optimization strategy that seeks to minimize the variance between the estimate pose and a known motion path. (See section 6.2.2.) The above differential equation represents a continuous integrated random walk, or an integrated *Wiener* or *Brownian-motion* process. Specifically, we model each component of the linear and angular HiBall velocities as random walks, and use these, assuming constant inter-measurement velocity, to estimate the six elements of the HiBall pose at time $t + \delta t$ as follows: $$\bar{x}(t+\delta t) = \begin{bmatrix} 1 & \delta t \\ 0 & 1 \end{bmatrix} \bar{x}(t). \qquad (1)$$ In addition to a relatively simple process model, the HiBall measurement model is relatively simple. For any Ceiling LED (section 4.1) and HiBall camera view (section 4.2), the 2D sensor measurement can be modeled as $$\begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} \bar{c}_x/\bar{c}_z \\ \bar{c}_y/\bar{c}_z \end{bmatrix} \qquad (2)$$

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CLAIM 3	HiBall
	where $$\begin{bmatrix}\bar{c}_x\\ \bar{c}_y\\ \bar{c}_z\end{bmatrix} = VR^T(\bar{l}_{xyz} - \bar{x}_{xyz}),$$ V is the camera viewing matrix from section 5.1, the vector $\bar{l}$ contains the position of the LED in the world, and R is a rotation matrix constructed from the orientation quaternion contained in the state vector: $$R = \text{rot\_from\_quat}(\bar{x}_q).$$ In practice we maintain the orientation of the HiBall as a combination of a global (external to the state) quaternion and a set of incremental angles as described in 128,291. Because the measurement model is non-linear we use an extended Kalman filter, making use of the Jacobian of the non-linear HiBall measurement model to transform the covariance of the Kalman filter. While this approach does not preserve the Gaussian nature of the covariance, it has been used successfully in countless applications since the introduction of the (linear) Kalman filter. Based on observations of the statistics of the HiBall filter residuals, the approach also appears to work well for the HiBall. At each estimation cycle, the next of the 26 possible views is chosen randomly. Four points corresponding to the comers of the LEPD sensor associated with that view are then projected into the world using the 3 by 4 viewing matrix for that view, along with the current estimates for the HiBall position and orientation. This projection, which is the inverse of the measurement relationship described above, results in four rays extending from the sensor into the world. The intersection of these rays and the approximate plane of the Ceiling determines a 2D bounding box on the Ceiling, within which are the candidate LEDs for the current camera view. One of the candidate LEDs is then chosen in a least-recently-used fashion to ensure a diversity of constraints. Once a particular view and LED have been chosen in this fashion, the CIB (section 4.3) is instructed to flash the LED and take a measurement as described in section 5.2. ***This single measurement is compared with a prediction obtained using (2), and the difference or residual is used to update the filter state and covariances using the Kalman gain matrix.*** The Kalman gain is computed as a combination of the current filter covariance, the measurement noise variance (section 6.2. l), and the Jacobian of the measurement model. A more detailed discussion of the HiBall Kalman filter and the SCAAT approach is beyond the scope of this paper. For additional information see [28,29]. Welch 1999 at 4-5.

CLAIM 3	HiBall
	5.2 On-Line HiBall Measurements Upon receiving a command from the CIB (section 4.3), which is synchronized with a CIB command to the ceiling, the HiBall selects the specified LEPD and performs three measurements, one before the beacon flashes, one during the beacon flash, and one after the beacon flash. Known as "dark-light-dark", this technique is used to subtract out DC bias, low frequency noise, and background light from the beacon signal. Each LEPD has four transimpedance amplifiers, the analog outputs of which are multiplexed with those of the other LEPDs, then sampled, held, and converted by four 16-bit Delta-Sigma ADCs. Multiple samples can be integrated internally in the HiBall. The digitized LEPD data are organized into a packet for communication back to the CIB. The packets also contain information to assist in error detection. The communication protocol is simple, and while presently implemented by wire, the modulation scheme is amenable to a wireless implementation. The present wired implementation allows multiple HiBalls to be daisy chained so a single cable can support a user with multiple HiBalls. During run time we attempt to maximize the signal-to-noise ratio of the measurement with an automatic gain control scheme. For each LED we store a target signal strength constant. We compute the LED current and number of integrations (of successive A/D samples) by dividing this strength constant by the square of the distance to the LED, estimated from the current position estimate. ***After a reading we look at the strength of the actual measurement. If it is larger than expected we reduce the gain, if it is less than expected we increase the gain. The increase and decrease are implemented as on-line averages with scaling such that the gain constant decreases rapidly (to avoid overflow) and increases slowly. Finally we use the measured signal strength to estimate the noise on the signal using [8], and then use this as the measurement noise estimate for the Kalman filter*** (section 5.3). Welch 1999 at 4. As a result of these improvements the HiBall Tracker can generate over 2000 estimates per second, with less than one millisecond of latency. The system exhibits sub-millimeter translation noise and similar measured accuracy, as well as less than 0.03 degrees of orientation noise with similar measured accuracy. The weight of the user-worn HiBall is about 300 grams, making it lighter than just one camera in the 1991 system. The working volume of the current system is greater than 90 cubic meters (greater than 45 square meters of floor space, greater than 2 meters of height variation). This area can be expanded by adding more tiles, or by using checkerboard configurations which spread tiles over a larger area. Welch 1999 at 2.

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CLAIM 3	HiBall
	Both parts of the camera model are determined using a calibration procedure that relies on a goniometer (an angular positioning system) of our own design. This device consists of two servo motors mounted together such that one motor provides rotation about the vertical axis while the second motor provides rotation about an axis orthogonal to vertical. An important characteristic of the goniometer is that the rotational axes of the two motors intersect at a point at the center of the HiBall optical sphere; this point is defined as the origin of the HiBall. (It is this origin that provides the reference for the HiBall state during run time as described in section 5.3.) The rotational positioning motors were rated to provide 20 arc-second precision; we further calibrated them using a surveying grade theodolite, an angle measuring system, to 6 arc seconds. In order to determine the mapping between sensor image plane coordinates and three-space rays, we use a single LED mounted at a fixed location in the laboratory such that it is centered in the view directly out of the top lens of the HiBall. This ray defines the Z or up axis for the HiBall coordinate system. We sample other rays by rotating the goniometer motors under computer control. We sample each view with rays spaced about every 6 minutes of arc throughout the field of view. We repeat each measurement 100 times in order to reduce the effects of noise on the individual measurements and to estimate the standard deviation of the measurements. Given the tables of approximately 2500 measurements for each view, we first determine a 3 by 4 view matrix using standard linear least-squares techniques. Then we determine the deviation of each measured point from that predicted by the ideal linear model. These deviations are re-sampled into a 25 by 25 grid indexed by sensor-plane coordinates using a simple scan conversion procedure and averaging. Given a measurement from a sensor at run time we convert it to an "ideal" measurement by subtracting a deviation bi-linearly interpolated from the nearest 4 entries in the table. Welch 1999 at 3 The HiBall tracker system (Figure 2) provides six-degree-of freedom tracking of devices in real time. An outward looking infrared-sensing subsystem called a HiBall (Figure 1, lower-right) is mechanically fixed to each device to be tracked. The HiBalls view an environment containing a subsystem of fixed-location infrared beacons which we call the Ceiling. At the present time, the beacons are in fact entirely located in the ceiling of our laboratory, but could as well be located in walls or other arbitrary fixed locations. These subsystems are coordinated by a Ceiling-HiBall Interface Board (CIB) which provides communication and synchronization functions between the host computer and the attached subsystems. Each HiBall has 26 narrow (less than 6 degree) views distributed over a large solid angle. Beacons are selectively flashed in a sequence such that they are seen by many different fields of view of each HiBall. Initial acquisition is performed using a brute force search through beacon space, but once initial lock is made, the selection of beacons to flash is tailored to the fields of view of the HiBalls. Tracking is maintained using a Kalman filter-based prediction-correction algorithm known as SCAAT. This technique has been further extended to provide self-calibration of the Ceiling on-line with the tracking of the attached HiBalls.

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CLAIM 3	HiBall
	Welch 1999 at 2. 4.2 The HiBall As can be seen in Figure 1 and color plate image Welch 1 the HiBall is a hollow ball having dodecahedral symmetry with lenses in the upper six faces and lateral effect photo diodes (LEPDs) on the insides of the opposing six lower faces. This immediately gives six primary fields of view, or camera systems which share the same internal air space, and whose adjacent directions of view are uniformly separated by 57 degrees. While the original intent of the shared internal air space was to save space, we subsequently realized that light entering any lens sufficiently off axis can be seen by an adjacent LEPD. As such, five secondary fields of view are provided by the top or central lens, and three secondary fields of view are provided by the five other lenses. Overall, this provides 26 fields of view which are used to sense widely separated groups of beacons in the environment. While these extra views complicate the initialization of the Kalman filter as described in section 5.5, they turn out to be of great benefit during steady-state tracking by effectively increasing the overall HiBall field of view without sacrificing resolution. Welch 1999 at 2-3. 4.3 The Ceiling-HiBall Interface Board The Ceiling-HiBall Interface Board (CIB), shown below in Figure 4, provides communication and synchronization between a host personal computer, the Ceiling (section 4.1) and the HiBall (section 4.2). The CIB has four Ceiling ports allowing interleaving of ceiling panels for up to four simultaneous led flashes and/or higher Ceiling bandwidth for more simultaneous hiball usage. (The Ceiling bandwidth is inherently limited by LED current restrictions as described in section 4.1, but this can be increased by spatially multiplexing the Ceiling tiles.) The CIB has two tether interfaces that can communicate with up to four daisy-chained hiballs each. The full-duplex communication with the hiballs uses a modulation scheme (BPSK) allowing future wireless operation. The interface from the CIB to the host PC is the stable IEEE1284C extended parallel port (EPP) standard. The CIB comprises analog drive and receive components as well as digital logic components. The digital components implement store and forward in both directions and synchronize the timing of the LED “on” interval within the HiBall dark-light-dark intervals. The protocol supports fullduplex flow control. The data are arranged into packets containing error detection to insure data quality. Welch 1999 at 3.

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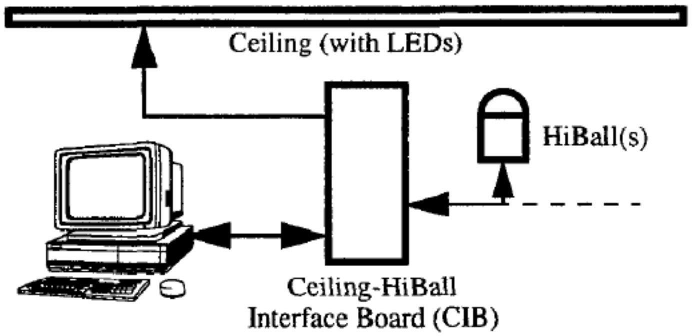
CLAIM 3	HiBall
	3. SYSTEM OVERVIEW  **Figure 2. A block diagram of the HiBall tracking system.** Welch 1999 at Fig. 2. The HiBall tracker system (Figure 2) provides six-degree-of freedom tracking of devices in real time. An outward looking infrared-sensing subsystem called a HiBall (Figure 1, lower-right) is mechanically fixed to each device to be tracked. The HiBalls view an environment containing a subsystem of fixed-location infrared beacons which we call the Ceiling. At the present time, the beacons are in fact entirely located in the ceiling of our laboratory, but could as well be located in walls or other arbitrary fixed locations. These subsystems are coordinated by a Ceiling-HiBall Interface Board (CIB) which provides communication and synchronization functions between the host computer and the attached subsystems. Each HiBall has 26 narrow (less than 6 degree) views distributed over a large solid angle. Beacons are selectively flashed in a sequence such that they are seen by many different fields of view of each HiBall. Initial acquisition is performed using a brute force search through beacon space, but once initial lock is made, the selection of beacons to flash is tailored to the fields of view of the HiBalls. Tracking is maintained using a Kalman filter-based prediction-correction algorithm known as SCAAT. This technique has been further extended to provide self-calibration of the Ceiling on-line with the tracking of the attached HiBalls. Welch 1999 at 2.

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CLAIM 3	HiBall

4.3 The Ceiling-HiBall Interface Board

The Ceiling-HiBall Interface Board (CIB), shown below in Figure 4, provides communication and synchronization between a host personal computer, the Ceiling (section 4.1) and the HiBall (section 4.2).

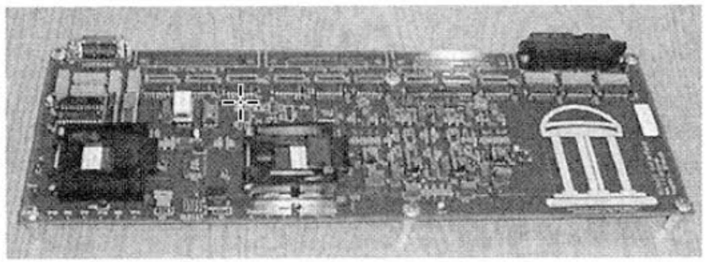

Figure 4. The Ceiling-HiBall Interface Board (CIB). The CIB shown is 19 inches, the newest revision is 14 inches.

Welch 1999 at 3.

HiBall-3000 Specifications and Performance

Hardware Components	
HiBall Optical Sensor(s)	2 7/8" tall, 2 1/8" diam, 6 OZ
Beacon Array Module (BAM)	Six 2' x 1" x 7/8" strips, 8 sq. ft.
PC-based Controller	Includes CIB I/F Board
Connections	Ethernet (VRPN), Serial (Standard Library Interface)
Software Components	
VR Peripheral Network (VRPN) support	Integrate system with other VR devices
Standard Library Interface	Compatible with existing systems
HBT Toolkit	Tools for set up, configuration and testing
HBT Library	Low-level system access
Output	Stream or point mode; XYZ coordinates; Quaternion, Euler angles or rotation matrices

3rdTech at 2.

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<table>
<tr><th>CLAIM 3</th><th>HiBall</th></tr>
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HiBall-3000 Wide-Area Tracker Features

• Very Wide Area	Scalable to over 1,600 sq.ft.
• High Precision	Ideal for augmented reality apps and rapid scene digitizing
• High-update, low latency	Solid, high-speed tracking; no "swimming"
• Small, light sensor	Head or stylus mountable
• Easy installation	Installs in standard drop-ceilings; requires no room modifications
• Multiple sensors	Multiple participants or head plus hand tracking
• No metal/sound interference	Requires no modification of the environment
• Accurate every-where	Consistent tracking near edges of space as well as in center

3rdTech at 2.

3. SYSTEM OVERVIEW

The HiBall Tracking System consists of three main components (Figure 6). An outward-looking sensing unit we call the *HiBall* is fixed to each user to be tracked. The HiBall unit observes a subsystem of fixed-location infrared LEDs we call the *Ceiling* 1. Communication and synchronization between the host computer and these subsystems is coordinated by the *Ceiling-HiBall Interface Board* (CIB). In Section 4 we describe these components in more detail. Each HiBall observes LEDs through multiple sensor-lens *views* that are distributed over a large solid angle. LEDs are sequentially flashed (one at a time) such that they are seen via a diverse set of views for each HiBall. Initial *acquisition* is performed using a brute force search through LED space, but once initial lock is made, the selection of LEDs to flash is tailored to the views of the active HiBall units. Pose estimates are maintained using a Kalman-filter-based prediction-correction approach known as *single-constraint-at-a-time* or SCAAT tracking. This technique has been extended to provide self-calibration of the Ceiling, concurrent with HiBall tracking. In Section 5 we describe the methods we employ, including the initial acquisition process and the SCAAT approach to pose estimation, with the *autocalibration* extension.

Welch HiBall at 6.

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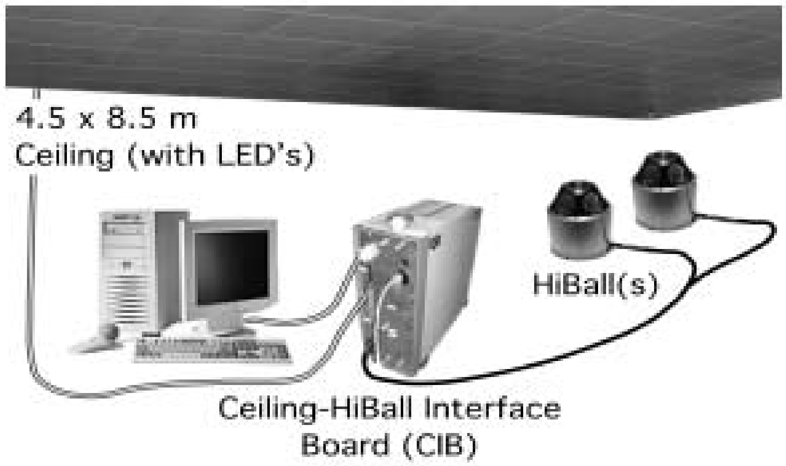
CLAIM 3	HiBall
	 Figure 6 Welch HiBall at Fig. 6. **4.3 The Ceiling-HiBall Interface Board** The Ceiling-HiBall Interface Board or CIB (Figure 11) provides communication and synchronization between a host personal computer, the HiBall (Section 4.1), and the Ceiling (Section 4.2). The CIB has four Ceiling ports allowing interleaving of ceiling panels for up to four simultaneous LED flashes and/or higher Ceiling bandwidth. (The Ceiling bandwidth is inherently limited by LED power restrictions as described in Section 4.2, but this can be increased by spatially multiplexing the Ceiling panels.) The CIB has two tether interfaces that can communicate with up to four daisy-chained HiBall units. The full-duplex communication with the HiBall units uses a modulation scheme (BPSK) allowing future wireless operation. The interface from the CIB to the host PC is the stable IEEE1284C extended parallel port (EPP) standard. The CIB comprises analog drive and receive components as well as digital logic components. The digital components implement store and forward in both directions and synchronize the timing of the LED "on" interval within the HiBall dark-light-dark intervals (Section 5.2). The protocol supports full-duplex flow control. The data are arranged into packets that incorporate error detection. Welch HiBall at 8-9.

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CLAIM 3	HiBall
	4. SYSTEM COMPONENTS **4.1 The HiBall** The original electro-optical tracker (Figure 3, bottom) used independently housed lateral effect photo-diode units (LEPDs) attached to a light-weight tubular framework. As it turns out, the mechanical framework would flex (distort) during use, contributing to estimation errors. In part to address this problem the HiBall sensor unit was designed as a single rigid hollow ball having dodecahedral symmetry, with lenses in the upper six faces and LEPD on the insides of the opposing six lower faces (Figure 7). This immediately gives six primary "camera" *views* uniformly spaced by 57 degrees. The views efficiently share the same internal air space, and are rigid with respect to each other. In addition, light entering any lens sufficiently off axis can be seen by a neighboring LEPD, giving rise to five secondary views through the top or central lens, and three secondary views through the five other lenses. Overall, this provides 26 fields of view which are used to sense widely separated groups of LEDs in the environment. While the extra views complicate the initialization of the Kalman filter as described in Section 5.5, they turn out to be of great benefit during steady-state tracking by effectively increasing the overall HiBall field of view without sacrificing optical sensor resolution. The lenses are simple plano-convex fixed-focus lenses. Infrared (IR) filtering is provided by fabricating the lenses themselves from RG-780 Schott glass filter material which is opaque to better than 0.001% for all visible wavelengths, and transmissive to better than 99% for IR wavelengths longer than 830 nm. The longwave filtering limit is provided by the DLS-4 LEPD silicon photodetector (UDT Sensors, Inc.) with peak responsivity at 950 nm but essentially blind above 1150 nm. The LEPDs themselves are not imaging devices; rather they detect the centroid of the luminous flux incident on the detector. The x-position of the centroid determines the ratio of two output currents, while the y-position determines the ratio of two other output currents. The total output current of each pair are commensurate, and proportional to the total incident flux. Consequently, focus is not an issue, so the simple fixed-focus lenses work well over a range of LED distances from about half a meter to infinity. The LEPDs and associated electronic components are mounted on a custom rigid-flex printed circuit board (Figure 8). This arrangement makes efficient use of the internal HiBall volume while maintaining isolation between analog and digital circuitry, and increasing reliability by alleviating the need for inter-component mechanical connectors. Figure 9 shows the physical arrangement of the folded electronics in the HiBall. Each LEPD has four transimpedance amplifiers (shown together as one "Amp" in Figure 9), the analog outputs of which are multiplexed with those of the other LEPDs, then sampled, held, and converted by four 16-bit Delta-Sigma

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CLAIM 3	HiBall
	analog-to-digital (A/D) converters. Multiple samples are integrated via an accumulator. The digitized LEPD data are organized into packets for communication back to the CIB. The packets also contain information to assist in error-detection. The communication protocol is simple, and while presently implemented by wire, the modulation scheme is amenable to a wireless implementation. The present wired implementation allows multiple HiBall units to be daisy-chained so a single cable can support a user with multiple HiBall units. Welch HiBall at 6-7. **1.3 The HiBall Tracking System** In this article we describe a new and vastly improved version of the 1991 system. We call the new system the *HiBall Tracking System*. Thanks to significant improvements in hardware and software this HiBall system offers unprecedented speed, resolution, accuracy, robustness, and flexibility. The bulky and heavy sensors and backpack of the previous system have been replaced by a small *HiBall* unit (Figure 4, bottom). In addition, the precisely machined LED ceiling panels of the previous system have been replaced by looser-tolerance panels that are relatively inexpensive to make and simple to install (Figure 4, top; Figure 10). Finally, we are using an unusual Kalman-filter-based algorithm that generates very accurate pose estimates at a high rate with low latency, and simultaneously self-calibrates the system. As a result of these improvements the HiBall Tracking System can generate over 2000 pose estimates per second, with less than one millisecond of latency, better than 0.5 millimeters and 0.03 degrees of absolute error and noise, everywhere in a 4.5 by 8.5 meter room (with over two meters of height variation). The area can be expanded by adding more panels, or by using checkerboard configurations which spread panels over a larger area. The weight of the user-worn HiBall is about 300 grams, making it lighter than one optical sensor in the 1991 system. Multiple HiBall units can be daisy chained together for head or hand tracking, pose-aware input devices, or precise 3D point. Welch HiBall at 4. The HiBall tracking system resolves linear motion of less than 0.2mm and angular motions under 0.03 degrees without the distortion seen in magnetic trackers. The update rate is greater than 1500 Hz and latency is about 1ms. To our knowledge, this was the first and remains the only demonstrated scalable tracking system for HMDs. UNC HiBall Tracker at 1. **The HiBall**

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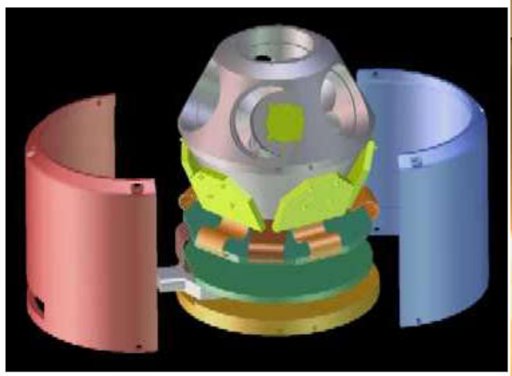
CLAIM 3	HiBall
	The HiBall is a cluster of 6 lenses and 6 photodiodes arranged so that each photodiodes can view LEDs through several of the 6 lenses, providing 26 view frustra originating at the HiBall. The assembly will include signal processing and A/D conversion circuitry. The total weight is about 5 ounces, making it lighter than just one of the cameras in the previous generation ceiling tracker. The HiBall and the ceiling panel are synchronized by a custom interface board which allows very high rate of LED sightings. The hardware alone can perform more than 3,000 sightings per second, while the whole system tracks using about 1,500. UNC HiBall Tracker at 1. **The Hiball** (Shown without lenses)   UNC HiBall Tracker at 2. **The SCAAT algorithm** The UNC HiBall Tracker relies on the SCAAT (Single Constraint At A Time) algorithm to compute the user's position and orientation from the individual sightings the HiBall makes of LEDs on the ceiling panels. The algorithm makes innovative use of an Extended Kalman Filter to provide position and orientation updates after each individual LED sighting, rather than after a group of several sightings as in the previous generation of UNC ceiling tracker. In addition, SCAAT improves on previously developed auto calibration techniques to allow on-line calibration as described below. For more information see Greg Welch's SCAAT page which includes links to

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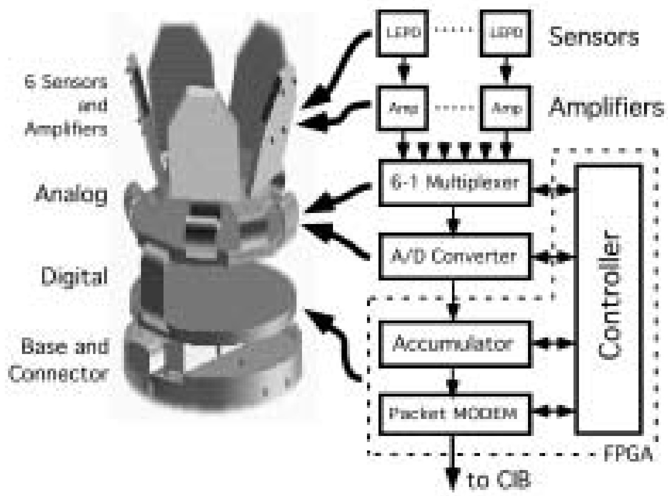
CLAIM 3	HiBall
	Greg Welch and Gary Bishop's 1997 SIGGRAPH paper on SCAAT. UNC HiBall Tracker at 2. **Autocalibration** The current ceiling's lower cost design was made possible by an auto calibration process described in Gottschalk93. The SCAAT algorithm improves on this by allowing auto calibration, tuning the actual LED positions, to be performed while the system is tracking. This accommodates shifts in the tiles and LEDs which can occur during normal use. In addition this technique opens possibilities for even less initial knowledge of LED placement than the current ceiling provides. As a test and demonstration of the autocalibration abilities of SCAAT, we have intentionally raised ceiling panels from their correct position. Here Dr. Gary Bishop is shown making the adjustments. The system was given only the initial flat LED positions, but after less than ten minutes of use (successfully tracking with the misplaced panels), SCAAT had accurately adjusted its knowledge of the LED positions through displacements more than 5cm. The above visualization shows the final measured LED positions. UNC HiBall Tracker at 2-3.  **Figure 9**

CLAIM 3	HiBall
	Welch HiBall at Fig. 9. **4.2 The Ceiling** As presently implemented, the infrared LEDs are packaged in 61 centimeter square *panels*, to fit a standard false ceiling grid (Figure 10, top). Each panel uses five printed circuit boards: a main controller board and four identical transverse-mounted *strips* (bottom). Each strip is populated with eight LEDs for a total of 32 LEDs per panel. We mount the assembly on top of a metal panel such that the LEDs protrude through 32 corresponding holes. The design results in a Ceiling with a rectangular LED pattern with periods of 7.6 and 15.2 centimeters. This spacing is used for the initial estimates of the LED positions in the lab, then during normal operation the SCAAT algorithm continually refines the LED position estimates (Section 5.4). The SCAAT *autocalibration* not only relaxes design and installation constraints, but provides greater precision in the face of initial and ongoing uncertainty in the Ceiling structure. We currently have enough panels to cover an area approximately 5.5 by 8.5 meters with a total of approximately 3,000 LEDs. 1 The panels are daisy-chained to each other, and panel selection encoding is position (rather than device) dependent. Operational commands are presented to the first panel of the daisy chain. At each panel, if the panel select code is zero the controller decodes and executes the operation; else it decrements the panel select code and passes it along to the next panel (controller). Upon decoding, a particular LED is selected and the LED is energized. The LED brightness (power) is selectable for *automatic gain control* as described in Section 5.2. We currently use Siemens SFH-487P GaAs LEDs which provide both a wide angle radiation pattern and high peak power, emitting at a center wavelength of 880 nm in the near IR. These devices can be pulsed up to 2.0 Amps for a maximum duration of 200 with a 1:50 (on:off) duty cycle. While the current Ceiling architecture allows flashing of only one LED at a time, LEDs may be flashed in any sequence. As such no single LED can be flashed too long or too frequently. We include both hardware and software protection to prevent this. **4.3 The Ceiling-HiBall Interface Board** The Ceiling-HiBall Interface Board or CIB (Figure 11) provides communication and synchronization between a host personal computer, the HiBall (Section 4.1), and the Ceiling (Section 4.2). The CIB has four Ceiling ports allowing interleaving of ceiling panels for up to four simultaneous LED flashes and/or higher Ceiling bandwidth. (The Ceiling bandwidth is inherently limited by LED power restrictions as described in Section 4.2, but this can be increased by spatially multiplexing the Ceiling panels.) The CIB has two tether interfaces that can communicate with up to four daisy-chained HiBall units. The full-duplex communication with the HiBall units uses a modulation scheme (BPSK) allowing future wireless operation. The interface from the CIB to the host PC is the stable IEEE1284C extended parallel port (EPP) standard. The CIB comprises analog drive and receive

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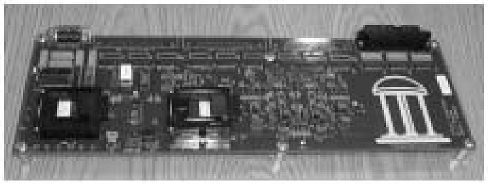
CLAIM 3	HiBall
	components as well as digital logic components. The digital components implement store and forward in both directions and synchronize the timing of the LED "on" interval within the HiBall dark-light-dark intervals (Section 5.2). The protocol supports full-duplex flow control. The data are arranged into packets that incorporate error detection. Welch HiBall at 8-9.  Figure 11 Welch HiBall at Fig. 11. **The SCAAT algorithm** The UNC HiBall Tracker relies on the SCAAT (Single Constraint At A Time) algorithm to compute the user's position and orientation from the individual sightings the HiBall makes of LEDs on the ceiling panels. The algorithm makes innovative use of an Extended Kalman Filter to provide position and orientation updates after each individual LED sighting, rather than after a group of several sightings as in the previous generation of UNC ceiling tracker. In addition, SCAAT improves on previously developed auto calibration techniques to allow on-line calibration as described below. For more information see Greg Welch's SCAAT page which includes links to Greg Welch and Gary Bishop's 1997 SIGGRAPH paper on SCAAT. UNC HiBall Tracker at 2. **Autocalibration** The current ceiling's lower cost design was made possible by an auto calibration process described in Gottschalk93. The SCAAT algorithm improves on this by allowing auto calibration, tuning the actual LED positions, to be performed while the system is tracking. This accommodates shifts in the tiles and LEDs which can occur during normal use. In addition this technique opens possibilities for even less initial knowledge of LED placement than the current ceiling provides.

CLAIM 3	HiBall
	As a test and demonstration of the autocalibration abilities of SCAAT, we have intentionally raised ceiling panels from their correct position. Here Dr. Gary Bishop is shown making the adjustments. The system was given only the initial flat LED positions, but after less than ten minutes of use (successfully tracking with the misplaced panels), SCAAT had accurately adjusted its knowledge of the LED positions through displacements more than 5cm. The above visualization shows the final measured LED positions. UNC HiBall Tracker at 2-3. **6.2.2 Complete System Simulations.** To produce realistic data for developing and tuning our algorithms we collected several motion paths *(*sequences of pose estimates) from our first generation electro-optical tracker (Figure 3) at its 70 Hz maximum report rate. These paths were recorded from both naive users visiting our monthly "demo days" and from experienced users in our labs. In the same fashion as we had done for (Azuma & Bishop, 1994a) we filtered the raw path data with a non-causal zero-phase-shift low-pass filter to eliminate energy above 2 Hz. The output of the low-pass filtering was then re-sampled at whatever rate we wanted to run the simulated tracker, usually 1000 Hz. For the purposes of our simulations we considered these resampled paths to be the "truth"—a perfect representation of a user's motion. Tracking error was determined by comparing the "true" path to the estimated path produced by the tracker. The simulator reads camera models describing the 26 views, the sensor noise parameters, the LED positions and their expected error, and the motion path described above. Before beginning the simulation, the LED positions are perturbed from their ideal positions by adding normally distributed error to each axis. Then, for each simulated cycle of operation, the "true" pose are updated using the input motion path. Next, a view is chosen and a visible LED within that view is selected, and the image-plane coordinates of the LED on the chosen sensor are computed using the camera model for the view and the LED as described in Section 5.3. These sensor coordinates are then perturbed based on the sensor noise model (Section 6.2.1) using the distance and angle to the LED. Now these noise corrupted sensor readings are fed to the SCAAT filter to produce an updated position estimate. The position estimate is compared to the true position to produce a scalar error metric described next. Welch HiBall at 16-17. **5.4 On-line LED Autocalibration** Along with the benefit of simplicity and speed, the SCAAT approach offers the additional capability of being able to estimate the 3D positions of the LEDs in the world concurrently with the pose of the HiBall, on line, in real time. This capability is a tremendous benefit in terms of the accuracy and noise characteristics of the estimates. Accurate LED position estimates are so important that prior to the introduction of the SCAAT approach a specialized off-line approach was developed to address the problem (Gottschalk & Hughes, 1993).

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CLAIM 3	HiBall
	The method we now use for autocalibration involves defining a distinct SCAAT Kalman filter for each LED. Specifically, for each LED we maintain a state $\bar{l}$ (estimate of the 3D position) and a 3x3 Kalman filter covariance. At the beginning of each estimation cycle we form an augmented state vector $\hat{x}$ using the appropriate LED state and the current HiBall state: $\hat{x} = [\bar{x}^{\mathrm{T}}, \bar{l}^{\mathrm{T}}]^{\mathrm{T}}$. Similarly we augment the Kalman filter error covariance matrix with that of the LED filter. We then follow the normal steps outlined in Section 5.3, with the result being that the LED portion of the filter state and covariance is updated in accordance with the measurement residual. At the end of the cycle we extract the LED portions of the state and covariance from the augmented filter, and save them externally. The effect is that as the system is being used, it continually refines its estimates of the LED positions, thereby continually improving its estimates of the HiBall pose. Again, for additional information see (Welch, 1996; Welch & Bishop, 1997). Welch HiBall at 13. The Kalman filter requires both a model of the process dynamics, and a model of the relationship between the process state and the available measurements. In part due to the simplicity of the SCAAT approach we are able to use a simple PV (position-velocity) process model (Brown & Hwang, 1992). Consider the simple example state vector $\bar{x}(t) = [x_p(t), x_v(t)]^{\mathrm{T}}$ where the first element $x_p(t)$ is the pose (position or orientation) and the second element $x_v(t)$ is the corresponding velocity, i.e. $x_v(t) = \frac{d}{dt}x_p(t)$. We model the continuous change in the HiBall state with the simple differential equation $$\frac{d}{dt}\bar{x}(t) = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} x_p(t) \\ x_v(t) \end{bmatrix} + \begin{bmatrix} 0 \\ \mu \end{bmatrix}u(t), \qquad (1)$$ where *u(t)* is a normally-distributed white (in the frequency spectrum) scalar noise process, and the scalar μ represents the magnitude or *spectral density* of the noise. We use a similar model with a distinct noise process for each of the six pose elements. We determine the individual noise magnitudes using an off-line simulation of the system and a non-linear optimization strategy that seeks to minimize the variance between the estimated pose and a known motion path. (See Section 6.2.2.) The differential equation (1) represents a continuous integrated random walk, or an integrated *Wiener* or *Brownian-motion* process. Specifically, we model each component of the linear and angular HiBall velocities as a random walk, and then use these (assuming constant inter-measurement velocity) to estimate the HiBall pose at time $t + \delta t$ as follows:

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CLAIM 3	HiBall
	$$\bar{x}(t+\delta t) = \begin{bmatrix} 1 & \delta t \\ 0 & 1 \end{bmatrix} \bar{x}(t) \qquad (2)$$ for each of the six pose elements. In addition to a relatively simple process model, the HiBall measurement model is relatively simple. For any Ceiling LED (Section 4.2) and HiBall view (Section 4.1), the 2D sensor measurement can be modeled as $$\begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} c_x/c_z \\ c_y/c_z \end{bmatrix} \qquad (3)$$ where $$\begin{bmatrix} c_x \\ c_y \\ c_z \end{bmatrix} = VR^{T}(\hat{l}_{xyz} - \bar{x}_{xyz}), \qquad (4)$$ is the camera viewing matrix from Section 5.1, is the position of the LED in the world, is the position of the HiBall in the world, and is a rotation matrix corresponding to the orientation of the HiBall in the world. In practice we maintain the orientation of the HiBall as a combination of a global (external to the state) quaternion and a set of incremental angles as described in (Welch, 1996; Welch & Bishop, 1997). Welch HiBall at 11-12. **5.2 On-Line HiBall Measurements** Upon receiving a command from the CIB (Section 4.3), which is synchronized with a CIB command to the ceiling, the HiBall selects the specified LEPD and performs three measurements, one before the LED flashes, one during the LED flash, and one after the LED flash. Known as “dark-light-dark”, this technique is used to subtract out DC bias, low frequency noise, and background light from the LED signal. We then convert the measured sensor coordinates to “ideal” coordinates using the calibration tables described in Section 5.1. In addition, during run time we attempt to maximize the signal-to-noise ratio of the measurement with an automatic gain control scheme. For each LED we store a target signal strength factor. We compute the LED current and number of integrations (of successive accumulated A/D samples) by dividing this strength factor by the square of the distance to the LED, estimated from the current position estimate. After a reading we look at the strength of the actual measurement. If it is larger than expected we reduce the gain, if it is less than expected we increase the gain. The increase and decrease are implemented as on-line averages with scaling such that the gain

CLAIM 3	HiBall
	factor decreases rapidly (to avoid overflow) and increases slowly. Finally we use the measured signal strength to estimate the noise on the signal using (Chi, 1995), and then use this as the measurement noise estimate for the Kalman filter (Section 5.3). Welch HiBall at 9-10. *See also* /hiball/src/libs/tracker and /cib, including but not limited to the following: "The ceiling performs computations of the LEPD and LED positions." /hiball/src/libs/tracker/ceiling.cpp /hiball/src/libs/tracker/ceiling.h /hiball/src/libs/tracker/tracker.h /hiball/src/libs/tracker/tracker.cpp *See also* Defendants' Invalidity Contentions for further discussion.

D. DEPENDENT CLAIM 4

CLAIM 4	HiBall
[4] The system of claim 2 wherein the interface enables the estimation subsystem to perform computations independently of an implementation of the sensor modules.	At least under Plaintiffs' apparent infringement theory, HiBall discloses, either expressly or inherently, the system of claim 2 wherein the interface enables the estimation subsystem to perform computations independently of an implementation of the sensor modules. In the alternative, this element would be obvious over HiBall in light of the other references disclosed in Defendants' Invalidity Contentions and/or the knowledge of one of ordinary skill in the art. *See, e.g.*:

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CLAIM 4	HiBall
	In contrast, the approach we use with the new HiBall system produces tracker reports as each new measurement is made rather than waiting to form a complete collection of observations. Because single measurements under-constrain the mathematical solution, we refer to the approach as Single-Constraint-at-a-Time or SCAAT tracking [28, 291. The key is that the single measurements provide some information about the user's state, and thus can be used to incrementally improve a previous estimate. Using a Kalman filter [15] we intentionally fuse measurements that do not individually provide sufficient information, incorporating each individual measurement immediately as it is obtained. With this approach we are able to generate estimates more frequently, with less latency, with improved accuracy, and we are able to effectively estimate the LED positions on-line concurrently while tracking the HiBall (section 5.4). We use a Kalman filter, a minimum variance stochastic estimator, to estimate the HiBall state 5, i.e. the position and orientation of the HiBall. We use a Kalman filter in part because the sensor measurement noise and the typical user motion dynamics can be modeled as normally-distributed random processes, but also because we want an efficient online method of estimation. A basic introduction to the Kalman filter can be found in Chapter 1 of [17], while a more complete introductory discussion can be found in [20], which also contains some interesting historical narrative. More extensive references can be found in [7,12,14,16,17, 301. The Kalman filter has been used previously to address similar or related problems. See for example [2, 3,9, 10, 18, 231, and most recently [113. The SCAAT approach on the other hand is an attempt to reverse this cycle. Because we intentionally use a single constraint per estimate, the algorithmic complexity is drastically reduced, which reduces the execution time, and hence the amount of motion between estimation cycles. Because the amount of motion is limited we are able to use a simple dynamic (process) model in the Kalman filter, which further simplifies the computations. In short, the simplicity of the approach means it can run very fast, which means it can produce estimates very rapidly, with low noise. The Kalman filter requires both a model of the process dynamics, and a model of the relationship between the process state and the available measurements. In part due to the simplicity of the SCAAT approach we are able to use a very simple process model. We model the continuous change in the HiBall state vector Z(t) with the simple differential equation

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CLAIM 4	HiBall
	$$\frac{d}{dt}\bar{x}(t) = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \bar{x}_1(t) \\ \bar{x}_2(t) \end{bmatrix} + \begin{bmatrix} 0 \\ \mu \end{bmatrix} u(t),$$ where the scalar $$\bar{x}_2(t) = \frac{d}{dt}\bar{x}_1(t),$$ $u(t)$ is a normally-distributed scalar white noise process, and the scalar μ represents the magnitude of the noise (the spectral density). A similar model with a distinct noise magnitude μ is used for each of the six position and orientation elements. The individual noise magnitudes are determined using an off-line simulation of the system and a non-linear optimization strategy that seeks to minimize the variance between the estimate pose and a known motion path. (See section 6.2.2.) The above differential equation represents a continuous integrated random walk, or an integrated *Wiener* or *Brownian-motion* process. Specifically, we model each component of the linear and angular HiBall velocities as random walks, and use these, assuming constant inter-measurement velocity, to estimate the six elements of the HiBall pose at time $t + \delta t$ as follows: $$\bar{x}(t + \delta t) = \begin{bmatrix} 1 & \delta t \\ 0 & 1 \end{bmatrix} \bar{x}(t). \quad (1)$$ In addition to a relatively simple process model, the HiBall measurement model is relatively simple. For any Ceiling LED (section 4.1) and HiBall camera view (section 4.2), the 2D sensor measurement can be modeled as $$\begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} \bar{c}_x / \bar{c}_z \\ \bar{c}_y / \bar{c}_z \end{bmatrix} \quad (2)$$

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CLAIM 4	HiBall
	where $$\begin{bmatrix} \bar{c}_x \\ \bar{c}_y \\ \bar{c}_z \end{bmatrix} = VR^T(\dot{l}_{xyz} - \bar{x}_{xyz}),$$ V is the camera viewing matrix from section 5.1, the vector $\dot{l}$ contains the position of the LED in the world, and R is a rotation matrix constructed from the orientation quaternion contained in the state vector: $$R = \text{rot\_from\_quat}(\bar{x}_q).$$ In practice we maintain the orientation of the HiBall as a combination of a global (external to the state) quaternion and a set of incremental angles as described in 128,291. Because the measurement model is non-linear we use an extended Kalman filter, making use of the Jacobian of the non-linear HiBall measurement model to transform the covariance of the Kalman filter. While this approach does not preserve the Gaussian nature of the covariance, it has been used successfully in countless applications since the introduction of the (linear) Kalman filter. Based on observations of the statistics of the HiBall filter residuals, the approach also appears to work well for the HiBall. At each estimation cycle, the next of the 26 possible views is chosen randomly. Four points corresponding to the comers of the LEPD sensor associated with that view are then projected into the world using the 3 by 4 viewing matrix for that view, along with the current estimates for the HiBall position and orientation. This projection, which is the inverse of the measurement relationship described above, results in four rays extending from the sensor into the world. The intersection of these rays and the approximate plane of the Ceiling determines a 2D bounding box on the Ceiling, within which are the candidate LEDs for the current camera view. One of the candidate LEDs is then chosen in a least-recently-used fashion to ensure a diversity of constraints. Once a particular view and LED have been chosen in this fashion, the CIB (section 4.3) is instructed to flash the LED and take a measurement as described in section 5.2. This single measurement is compared with a prediction obtained using (2), and the difference or residual is used to update the filter state and covariances using the Kalman gain matrix. The Kalman gain is computed as a combination of the current filter covariance, the measurement noise variance (section 6.2. l), and the Jacobian of the measurement model. A more detailed discussion of the HiBall Kalman filter and the SCAAT approach is beyond the scope of this paper. For additional information see [28,29]. Welch 1999 at 4-5.

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CLAIM 4	HiBall
	5.2 On-Line HiBall Measurements Upon receiving a command from the CIB (section 4.3), which is synchronized with a CIB command to the ceiling, the HiBall selects the specified LEPD and performs three measurements, one before the beacon flashes, one during the beacon flash, and one after the beacon flash. Known as "dark-light-dark"***, this technique is used to subtract out DC bias, low frequency noise, and background light from the beacon signal.*** Each LEPD has four transimpedance amplifiers, the analog outputs of which are multiplexed with those of the other LEPDs, then sampled, held, and converted by four 16-bit Delta-Sigma ADCs. Multiple samples can be integrated internally in the HiBall. The digitized LEPD data are organized into a packet for communication back to the CIB. The packets also contain information to assist in error detection. The communication protocol is simple, and while presently implemented by wire, the modulation scheme is amenable to a wireless implementation. The present wired implementation allows multiple HiBalls to be daisy chained so a single cable can support a user with multiple HiBalls. During run time we attempt to maximize the signal-to-noise ratio of the measurement with an automatic gain control scheme. For each LED we store a target signal strength constant. We compute the LED current and number of integrations (of successive A/D samples) by dividing this strength constant by the square of the distance to the LED, estimated from the current position estimate. ***After a reading we look at the strength of the actual measurement. If it is larger than expected we reduce the gain, if it is less than expected we increase the gain. The increase and decrease are implemented as on-line averages with scaling such that the gain constant decreases rapidly (to avoid overflow) and increases slowly***. Finally we use the measured signal strength to estimate the noise on the signal using [8], and then use this as the measurement noise estimate for the Kalman filter (section 5.3). Welch 1999 at 4. As a result of these improvements the HiBall Tracker can generate over 2000 estimates per second, with less than one millisecond of latency. The system exhibits sub-millimeter translation noise and similar measured accuracy, as well as less than 0.03 degrees of orientation noise with similar measured accuracy. The weight of the user-worn HiBall is about 300 grams, making it lighter than just one camera in the 1991 system. The working volume of the current system is greater than 90 cubic meters (greater than 45 square meters of floor space, greater than 2 meters of height variation). This area can be expanded by adding more tiles, or by using checkerboard configurations which spread tiles over a larger area. Welch 1999 at 2.

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CLAIM 4	HiBall
	Both parts of the camera model are determined using a calibration procedure that relies on a goniometer (an angular positioning system) of our own design. This device consists of two servo motors mounted together such that one motor provides rotation about the vertical axis while the second motor provides rotation about an axis orthogonal to vertical. An important characteristic of the goniometer is that the rotational axes of the two motors intersect at a point at the center of the HiBall optical sphere; this point is defined as the origin of the HiBall. (It is this origin that provides the reference for the HiBall state during run time as described in section 5.3.) The rotational positioning motors were rated to provide 20 arc-second precision; we further calibrated them using a surveying grade theodolite, an angle measuring system, to 6 arc seconds. In order to determine the mapping between sensor image plane coordinates and three-space rays, we use a single LED mounted at a fixed location in the laboratory such that it is centered in the view directly out of the top lens of the HiBall. This ray defines the Z or up axis for the HiBall coordinate system. ***We sample other rays by rotating the goniometer motors under computer control. We sample each view with rays spaced about every 6 minutes of arc throughout the field of view. We repeat each measurement 100 times in order to reduce the effects of noise on the individual measurements and to estimate the standard deviation of the measurements***. Given the tables of approximately 2500 measurements for each view, we first determine a 3 by 4 view matrix using standard linear least-squares techniques. Then we determine the deviation of each measured point from that predicted by the ideal linear model. These deviations are re-sampled into a 25 by 25 grid indexed by sensor-plane coordinates using a simple scan conversion procedure and averaging. Given a measurement from a sensor at run time we convert it to an "ideal" measurement by subtracting a deviation bi-linearly interpolated from the nearest 4 entries in the table. Welch 1999 at 3 The HiBall tracker system (Figure 2) provides six-degree-of freedom tracking of devices in real time. An outward looking infrared-sensing subsystem called a HiBall (Figure 1, lower-right) is mechanically fixed to each device to be tracked. The HiBalls view an environment containing a subsystem of fixed-location infrared beacons which we call the Ceiling. At the present time, the beacons are in fact entirely located in the ceiling of our laboratory, but could as well be located in walls or other arbitrary fixed locations. These subsystems are coordinated by a Ceiling-HiBall Interface Board (CIB) which provides communication and synchronization functions between the host computer and the attached subsystems. Each HiBall has 26 narrow (less than 6 degree) views distributed over a large solid angle. Beacons are selectively flashed in a sequence such that they are seen by many different fields of view of each HiBall. Initial acquisition is performed using a brute force search through beacon space, but once initial lock is made, the selection of beacons to flash is tailored to the fields of view of the HiBalls. Tracking is maintained using a Kalman filter-based prediction-correction algorithm known as SCAAT. This technique has been further extended to provide self-calibration of the Ceiling on-line with the tracking of the attached HiBalls.

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CLAIM 4	HiBall
	Welch 1999 at 2. 4.2 The HiBall As can be seen in Figure 1 and color plate image Welch 1 the HiBall is a hollow ball having dodecahedral symmetry with lenses in the upper six faces and lateral effect photo diodes (LEPDs) on the insides of the opposing six lower faces. This immediately gives six primary fields of view, or camera systems which share the same internal air space, and whose adjacent directions of view are uniformly separated by 57 degrees. While the original intent of the shared internal air space was to save space, we subsequently realized that light entering any lens sufficiently off axis can be seen by an adjacent LEPD. As such, five secondary fields of view are provided by the top or central lens, and three secondary fields of view are provided by the five other lenses. Overall, this provides 26 fields of view which are used to sense widely separated groups of beacons in the environment. While these extra views complicate the initialization of the Kalman filter as described in section 5.5, they turn out to be of great benefit during steady-state tracking by effectively increasing the overall HiBall field of view without sacrificing resolution. Welch 1999 at 2-3. 4.3 The Ceiling-HiBall Interface Board The Ceiling-HiBall Interface Board (CIB), shown below in Figure 4, provides communication and synchronization between a host personal computer, the Ceiling (section 4.1) and the HiBall (section 4.2). The CIB has four Ceiling ports allowing interleaving of ceiling panels for up to four simultaneous led flashes and/or higher Ceiling bandwidth for more simultaneous hiball usage. (The Ceiling bandwidth is inherently limited by LED current restrictions as described in section 4.1, but this can be increased by spatially multiplexing the Ceiling tiles.) The CIB has two tether interfaces that can communicate with up to four daisy-chained hiballs each. The full-duplex communication with the hiballs uses a modulation scheme (BPSK) allowing future wireless operation. The interface from the CIB to the host PC is the stable IEEE1284C extended parallel port (EPP) standard. The CIB comprises analog drive and receive components as well as digital logic components. The digital components implement store and forward in both directions and synchronize the timing of the LED "on" interval within the HiBall dark-light-dark intervals. The protocol supports fullduplex flow control. The data are arranged into packets containing error detection to insure data quality. Welch 1999 at 3.

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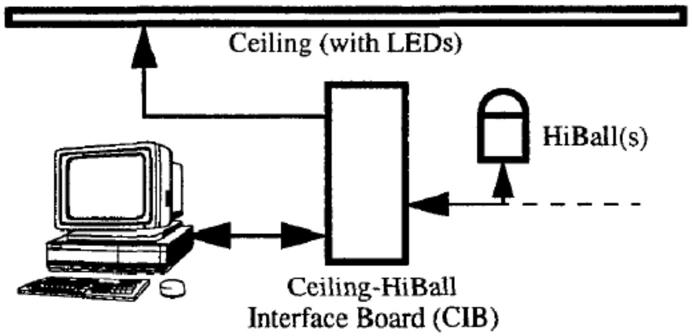
CLAIM 4	HiBall
	3. SYSTEM OVERVIEW  **Figure 2. A block diagram of the HiBall tracking system.** Welch 1999 at Fig. 2. The HiBall tracker system (Figure 2) provides six-degree-of freedom tracking of devices in real time. An outward looking infrared-sensing subsystem called a HiBall (Figure 1, lower-right) is mechanically fixed to each device to be tracked. The HiBalls view an environment containing a subsystem of fixed-location infrared beacons which we call the Ceiling. At the present time, the beacons are in fact entirely located in the ceiling of our laboratory, but could as well be located in walls or other arbitrary fixed locations. These subsystems are coordinated by a Ceiling-HiBall Interface Board (CIB) which provides communication and synchronization functions between the host computer and the attached subsystems. Each HiBall has 26 narrow (less than 6 degree) views distributed over a large solid angle. Beacons are selectively flashed in a sequence such that they are seen by many different fields of view of each HiBall. Initial acquisition is performed using a brute force search through beacon space, but once initial lock is made, the selection of beacons to flash is tailored to the fields of view of the HiBalls. Tracking is maintained using a Kalman filter-based prediction-correction algorithm known as SCAAT. This technique has been further extended to provide self-calibration of the Ceiling on-line with the tracking of the attached HiBalls. Welch 1999 at 2.

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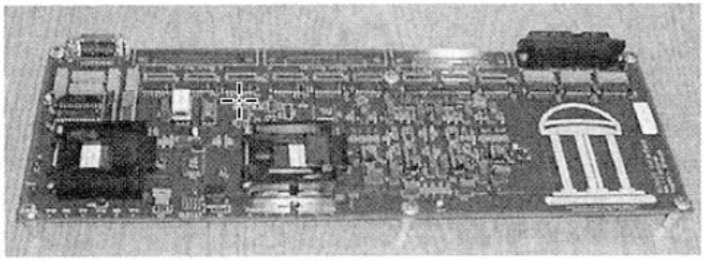
CLAIM 4	HiBall
	4.3 The Ceiling-HiBall Interface Board The Ceiling-HiBall Interface Board (CIB), shown below in Figure 4, provides communication and synchronization between a host personal computer, the Ceiling (section 4.1) and the HiBall (section 4.2).  **Figure 4. The Ceiling-HiBall Interface Board (CIB). The CIB shown is 19 inches, the newest revision is 14 inches.** Welch 1999 at 3. **The HiBall-3000 Optical Sensor** The HiBall-3000 tracker system is composed of two key integrated components; the HiBall Optical Sensor and the HiBall Ceiling Beacon Arrays. The HiBall Optical Sensor is composed of 6 lenses and photodiodes arranged so that each photodiode can 'view' infrared LEDs, in the Beacon Arrays mounted on the ceiling, through several of the 6 lenses. The assembly includes signal processing and analog-to-digital conversion circuitry. The total weight is about 6 ounces, making it light enough to comfortably mount on a headmounted display or hand-held device. By locating the sensors on the person or object being tracked — *inside-out tracking* — sensitivity around the working area is increased and the tracker area scales almost without limit. An entire lab, movie set, or assembly area can be tracked. The HiBall can also be mounted on a small probe or stylus, enabling extremely accurate measurements of individual objects within a large space. For example, this can be used for very rapid measurement of actual television or movie sets or other real-world objects to be combined with virtual scenes. No other device can provide comparable speed and accuracy over a wide area. 3rdTech at 1. **HiBall Beacon Array Modules**

Exhibit E-11

CLAIM 4	HiBall
	The infrared LEDs 'seen' by the HiBall Sensor are embedded in a series of ceiling mounted strips forming a 2D Beacon Array - 8 LEDs per strip; 6 strips per Beacon Array Module (BAM). These strips are designed to slip easily into a typical 'drop ceiling' with no changes required in panels, lights, vents, etc. - the more BAMs employed, the greater the range of the tracker. The arrays are highly modular — available in configurations covering as little as 64 square feet (8' x 8') or more than 1,600 square feet (40' x 40'). And no special adjustments are required to the ceiling structure — the system's precision is unaffected by typical variations in ceiling height. The HiBall Sensor and the Beacon Arrays are synchronized by a Ceiling- HiBall Interface Board (CIB), part of the system's integrated PC, which enables extremely high rates of LED 'sightings'— approximately 2,000 per second. This results in a tracker update rate of 2,000 Hz — several times faster than other commercially available wide-area trackers. Faster updates means lower latency and more accurate tracking - even with rapid movements. **AutoCalibration** The system makes use of a *single constraint at a time* (SCAAT) algorithm to compute the location and orientation of the HiBall Sensor at every LED sighting. In addition, the system incorporates *auto-calibration* — tuning the modeled location of individual LEDs on every update. This accommodates typical shifts and movements in the ceiling tiles and BAMs without loss of accuracy or performance. **Applications** The range and performance of the HiBall-3000 Tracker open up new possibilities for large-scale virtual reality such as exploring full-size architectural designs or engineering prototypes. Its precision enables largescale augmented reality for applications in medicine, training and entertainment where accurate correspondence between physical reality and the virtual world are critical. **Proven Results** Developed in the Computer Science Department of the University of North Carolina at Chapel Hill (see www.cs.unc.edu/~tracker), the original HiBall tracker has been in use since 1997 and has consistently exceeded performance expectations. 3rdTech at 1.

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CLAIM 4	HiBall

HiBall-3000 Specifications and Performance

Hardware Components

HiBall Optical Sensor(s)	2 7/8" tall, 2 1/8" diam, 6 OZ
Beacon Array Module (BAM)	Six 2' x 1" x 7/8" strips, 8 sq. ft.
PC-based Controller	Includes CIB I/F Board
Connections	Ethernet (VRPN), Serial (Standard Library Interface)

Software Components

VR Peripheral Network (VRPN) support	Integrate system with other VR devices
Standard Library Interface	Compatible with existing systems
HBT Toolkit	Tools for set up, configuration and testing
HBT Library	Low-level system access
Output	Stream or point mode; XYZ coordinates; Quaternion, Euler angles or rotation matrices

3rdTech at 2.

HiBall-3000 Wide-Area Tracker Features

• Very Wide Area	Scalable to over 1,600 sq.ft.
• High Precision	Ideal for augmented reality apps and rapid scene digitizing
• High-update, low latency	Solid, high-speed tracking; no "swimming"
• Small, light sensor	Head or stylus mountable
• Easy installation	Installs in standard drop-ceilings; requires no room modifications
• Multiple sensors	Multiple participants or head plus hand tracking
• No metal/sound interference	Requires no modification of the environment
• Accurate every-where	Consistent tracking near edges of space as well as in center

3rdTech at 2.

The SCAAT algorithm

The UNC HiBall Tracker relies on the SCAAT (Single Constraint At A Time) algorithm to compute the user's position and orientation from the individual sightings the HiBall makes of LEDs on the ceiling panels. The algorithm makes innovative use of an Extended Kalman Filter to provide position and orientation updates after each individual LED sighting, rather than after a group of several sightings as in the previous generation of UNC ceiling tracker. In addition, SCAAT improves on previously developed auto calibration techniques to allow on-

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CLAIM 4	HiBall
	line calibration as described below. For more information see Greg Welch's SCAAT page which includes links to Greg Welch and Gary Bishop's 1997 SIGGRAPH paper on SCAAT. UNC HiBall Tracker at 2. **Autocalibration** The current ceiling's lower cost design was made possible by an auto calibration process described in Gottschalk93. The SCAAT algorithm improves on this by allowing auto calibration, tuning the actual LED positions, to be performed while the system is tracking. This accommodates shifts in the tiles and LEDs which can occur during normal use. In addition this technique opens possibilities for even less initial knowledge of LED placement than the current ceiling provides. As a test and demonstration of the autocalibration abilities of SCAAT, we have intentionally raised ceiling panels from their correct position. Here Dr. Gary Bishop is shown making the adjustments. The system was given only the initial flat LED positions, but after less than ten minutes of use (successfully tracking with the misplaced panels), SCAAT had accurately adjusted its knowledge of the LED positions through displacements more than 5cm. The above visualization shows the final measured LED positions. UNC HiBall Tracker at 2-3. **6.2.2 Complete System Simulations.** To produce realistic data for developing and tuning our algorithms we collected several motion paths *(*sequences of pose estimates) from our first generation electro-optical tracker (Figure 3) at its 70 Hz maximum report rate. These paths were recorded from both naive users visiting our monthly "demo days" and from experienced users in our labs. In the same fashion as we had done for (Azuma & Bishop, 1994a) we filtered the raw path data with a non-causal zero-phase-shift low-pass filter to eliminate energy above 2 Hz. The output of the low-pass filtering was then re-sampled at whatever rate we wanted to run the simulated tracker, usually 1000 Hz. For the purposes of our simulations we considered these resampled paths to be the "truth"—a perfect representation of a user's motion. Tracking error was determined by comparing the "true" path to the estimated path produced by the tracker. The simulator reads camera models describing the 26 views, the sensor noise parameters, the LED positions and their expected error, and the motion path described above. Before beginning the simulation, the LED positions are perturbed from their ideal positions by adding normally distributed error to each axis. Then, for each simulated cycle of operation, the "true" pose are updated using the input motion path. Next, a view is chosen and a visible LED within that view is selected, and the image-plane coordinates of the LED on the chosen sensor are computed using the camera model for the view and the LED as described in Section 5.3. These sensor coordinates are then perturbed based on the sensor noise model (Section 6.2.1) using the distance and angle to the

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	LED. Now these noise corrupted sensor readings are fed to the SCAAT filter to produce an updated position estimate. The position estimate is compared to the true position to produce a scalar error metric described next. Welch HiBall at 16-17. **5.4 On-line LED Autocalibration** Along with the benefit of simplicity and speed, the SCAAT approach offers the additional capability of being able to estimate the 3D positions of the LEDs in the world concurrently with the pose of the HiBall, on line, in real time. This capability is a tremendous benefit in terms of the accuracy and noise characteristics of the estimates. Accurate LED position estimates are so important that prior to the introduction of the SCAAT approach a specialized off-line approach was developed to address the problem (Gottschalk & Hughes, 1993). The method we now use for autocalibration involves defining a distinct SCAAT Kalman filter for each LED. Specifically, for each LED we maintain a state $\bar{l}$ (estimate of the 3D position) and a 3x3 Kalman filter covariance. At the beginning of each estimation cycle we form an augmented state vector $\hat{x}$ using the appropriate LED state and the current HiBall state: $\hat{x} = [\bar{x}^{\mathrm{T}}, \bar{l}^{\mathrm{T}}]^{\mathrm{T}}$. Similarly we augment the Kalman filter error covariance matrix with that of the LED filter. We then follow the normal steps outlined in Section 5.3, with the result being that the LED portion of the filter state and covariance is updated in accordance with the measurement residual. At the end of the cycle we extract the LED portions of the state and covariance from the augmented filter, and save them externally. The effect is that as the system is being used, it continually refines its estimates of the LED positions, thereby continually improving its estimates of the HiBall pose. Again, for additional information see (Welch, 1996; Welch & Bishop, 1997). Welch HiBall at 13. The Kalman filter requires both a model of the process dynamics, and a model of the relationship between the process state and the available measurements. In part due to the simplicity of the SCAAT approach we are able to use a simple PV (position-velocity) process model (Brown & Hwang, 1992). Consider the simple example state vector $\bar{x}(t) = [x_p(t), x_v(t)]^{\mathrm{T}}$ where the first element $x_p(t)$ is the pose (position or orientation) and the second element $x_v(t)$ is the corresponding velocity, i.e. $x_v(t) = \frac{d}{dt}x_p(t)$. We model the continuous change in the HiBall state with the simple differential equation $$\frac{d}{dt}\bar{x}(t) = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x_p(t) \\ x_v(t) \end{bmatrix} + \begin{bmatrix} 0 \\ \mu \end{bmatrix} u(t), \qquad (1)$$

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	where *u(t)* is a normally-distributed white (in the frequency spectrum) scalar noise process, and the scalar μ represents the magnitude or *spectral density* of the noise. We use a similar model with a distinct noise process for each of the six pose elements. We determine the individual noise magnitudes using an off-line simulation of the system and a non-linear optimization strategy that seeks to minimize the variance between the estimated pose and a known motion path. (See Section 6.2.2.) The differential equation (1) represents a continuous integrated random walk, or an integrated *Wiener* or *Brownian-motion* process. Specifically, we model each component of the linear and angular HiBall velocities as a random walk, and then use these (assuming constant inter-measurement velocity) to estimate the HiBall pose at time $t + \delta t$ as follows: $$\bar{x}(t+\delta t) = \begin{bmatrix} 1 & \delta t \\ 0 & 1 \end{bmatrix} \bar{x}(t) \qquad (2)$$ for each of the six pose elements. In addition to a relatively simple process model, the HiBall measurement model is relatively simple. For any Ceiling LED (Section 4.2) and HiBall view (Section 4.1), the 2D sensor measurement can be modeled as $$\begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} c_x/c_z \\ c_y/c_z \end{bmatrix} \qquad (3)$$ where $$\begin{bmatrix} c_x \\ c_y \\ c_z \end{bmatrix} = VR^{T}(\hat{l}_{xyz} - \bar{x}_{xyz}), \qquad (4)$$ is the camera viewing matrix from Section 5.1, is the position of the LED in the world, is the position of the HiBall in the world, and is a rotation matrix corresponding to the orientation of the HiBall in the world. In practice we maintain the orientation of the HiBall as a combination of a global (external to the state) quaternion and a set of incremental angles as described in (Welch, 1996; Welch & Bishop, 1997). Welch HiBall at 11-12. **5.2 On-Line HiBall Measurements** Upon receiving a command from the CIB (Section 4.3), which is synchronized with a CIB command to the ceiling, the HiBall selects the specified LEPD and performs three measurements, one before the LED flashes, one during the LED flash, and one after the LED flash. Known as "dark-light-dark", this technique is used to subtract

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	out DC bias, low frequency noise, and background light from the LED signal. We then convert the measured sensor coordinates to "ideal" coordinates using the calibration tables described in Section 5.1. In addition, during run time we attempt to maximize the signal-to-noise ratio of the measurement with an automatic gain control scheme. For each LED we store a target signal strength factor. We compute the LED current and number of integrations (of successive accumulated A/D samples) by dividing this strength factor by the square of the distance to the LED, estimated from the current position estimate. After a reading we look at the strength of the actual measurement. If it is larger than expected we reduce the gain, if it is less than expected we increase the gain. The increase and decrease are implemented as on-line averages with scaling such that the gain factor decreases rapidly (to avoid overflow) and increases slowly. Finally we use the measured signal strength to estimate the noise on the signal using (Chi, 1995), and then use this as the measurement noise estimate for the Kalman filter (Section 5.3). Welch HiBall at 9-10. *See also* /hiball/src/libs/tracker and /cib, including but not limited to the following: "Acquire's job is to locate the hiball well enough that a Kalman Filter can be started which converges on the position. The initial location is done with search the ceiling for any sighted LED and then a series of steps to disambiguate the sighting (between shared views)." /hiball/src/libs/tracker/flacquire.cpp /hiball/src/libs/tracker/flacquire.h /hiball/src/libs/tracker/acquire.cpp /hiball/src/libs/tracker/acquire.h /hiball/src/libs/tracker/chooser.h /hiball/src/libs/tracker/chooser.cpp /hiball/src/libs/tracker/hiballfilter.h

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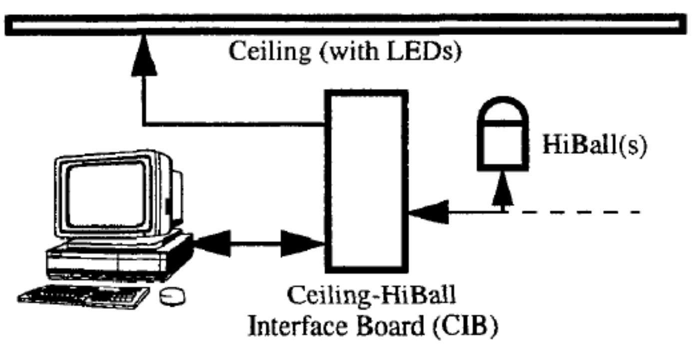
	/hiball/src/libs/tracker/hiballfilter.cpp *See also* Defendants' Invalidity Contentions for further discussion.

E. INDEPENDENT CLAIM 6

CLAIM 6	HiBall
[6.pre] A method comprising:	At least under Plaintiffs' apparent infringement theory, HiBall discloses, either expressly or inherently, a method. In the alternative, this element would be obvious over HiBall in light of the other references disclosed in Defendants' Invalidity Contentions and/or the knowledge of one of ordinary skill in the art. *See, e.g.*: **3. SYSTEM OVERVIEW**  **Figure 2. A block diagram of the HiBall tracking system.** Welch 1999 at Fig. 2.

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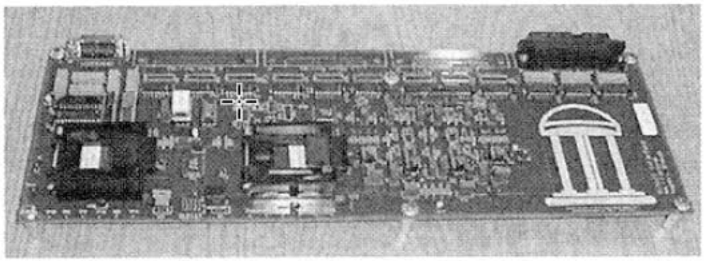
	The HiBall tracker system (Figure 2) provides six-degree-of freedom tracking of devices in real time. An outward looking infrared-sensing subsystem called a HiBall (Figure 1, lower-right) is mechanically fixed to each device to be tracked. The HiBalls view an environment containing a subsystem of fixed-location infrared beacons which we call the Ceiling. At the present time, the beacons are in fact entirely located in the ceiling of our laboratory, but could as well be located in walls or other arbitrary fixed locations. These subsystems are coordinated by a Ceiling-HiBall Interface Board (CIB) which provides communication and synchronization functions between the host computer and the attached subsystems. Each HiBall has 26 narrow (less than 6 degree) views distributed over a large solid angle. Beacons are selectively flashed in a sequence such that they are seen by many different fields of view of each HiBall. Initial acquisition is performed using a brute force search through beacon space, but once initial lock is made, the selection of beacons to flash is tailored to the fields of view of the HiBalls. Tracking is maintained using a Kalman filter-based prediction-correction algorithm known as SCAAT. This technique has been further extended to provide self-calibration of the Ceiling on-line with the tracking of the attached HiBalls. Welch 1999 at 2. **4.3 The Ceiling-HiBall Interface Board** The Ceiling-HiBall Interface Board (CIB), shown below in Figure 4, provides communication and synchronization between a host personal computer, the Ceiling (section 4.1) and the HiBall (section 4.2).  **Figure 4. The Ceiling-HiBall Interface Board (CIB). The CIB shown is 19 inches, the newest revision is 14 inches.** Welch 1999 at 3.

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	As part of an ongoing effort to develop a system that avoids such tradeoffs, the Tracker Research Group at the University of North Carolina (http:/ /www.cs.unc.edu/-tracker) has created a wide-area optoelectronic tracking technology that lets users move freely through full-scale virtual worlds in real time. Such a capability not only enables VR applications that would otherwise be difficult or impossible to achieve-such as the exploration of life-size architectural designs and room-filling molecular models-but it is also expected to be of value to augmented reality (AR). In AR, real and digital worlds are superimposed into one scene through the use of see-through head-mounted displays that rely either on mirrors to represent the physical world or video input. Highly accurate motion tracking is crucial because even small tracking errors can result in unacceptable misregistration between real and virtual objects. Called the HiBall Tracking System, the new technology is able to meet the needs of such applications through its implementation of four unique components: ceiling panels that house LED targets, a miniature optical- sensor cluster (the HiBall) that senses and digitizes the LED flashes, a custom interface board that facilitates communications among the various components of the system, and tracking software that processes the communications in real time. On the Right Track at 2. **Inside-Out Tracking** Unlike traditional optical tracking methods, in which targets are attached to the object or person to be tracked and sensed by a camera in the environment, the HiBall system employs an "inside-out" approach, in which the sensors are user mounted and the LED targets are fixed in the environment. This distinction is important, says UNC research assistant professor Greg Welch, because it ensures constant sensitivity to orientation over the working area. Also, because the targets are in the ceiling tiles, the tracking environment is infinitely scalable by increasing the number of tiles. The HiBall itself is unique in that it does not rely on the same charged-couple devices (CCDs) that most digital cameras employ. Rather, it uses lateral-effect photo diodes (LEPDs). Unlike CCD's, LEPDs are not imaging devices. They are 2D optical sensors that produce four analog voltages, which together indicate the 2D position of the center of the light hitting the sensor. "There is no image to capture and interpret, simply four voltages to digitize, which is done right inside the HiBall;' says Welch. The control center of the tracking system is the Ceiling-HiBall Interface Board (CIB), which sends LED addresses and control signals to the ceiling to direct the flashing of the LEDs. It also communicates with the HiBall, sending control signals and receiving the digitized LEPD values. The PC tracking software sends requests to the CIB for a sample of a particular ceiling LED from a particular optical sensor. In response, the CIB tells the ceiling to flash the LED and tells the HiBall to sample the LEPD. The digitized LEPD data it receives is sent back to the PC. The system's tracking code

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	relies on an estimation approach called SCAAT (single constraint at a time) tracking, which turns the individual LED sightings into a complete position and orientation, or pose, estimate for the HiBall. With SCAAT, individual observations are reported as soon as they're acquired, rather than at the end of a complete collection of measurements, providing some information about the user's pose. Subsequent measurements build on previous ones to improve the estimates. A filtering technique fuses a continuous sequence of these incomplete, single LED sightings into an ongoing sequence of complete estimates. To enhance the quality of the estimates and ensure low latency, thousands of LED sightings are generated per second. An autocalibration process compensates for shifts in the tiles and for inherent estimate inaccuracies. On the agenda for the HiBall system is the development of a wireless capability between the HiBall and the CIB. The researchers are also investigating more flexible LED strategies, including LED strips that can be hung from ceilings wherever needed. The group's long-term objective is to develop hybrid tracking approaches that will reduce the system's infrastructure to allow users to move beyond the lab, eventually outdoors, while maintaining system performance. In the meantime, the existing HiBall technology is headed toward commercialization by a new company called HiBall Tracker Inc., which is currently negotiating a technology license with UNC Chapel Hill. On the Right Track at 2. **The HiBall-3000 Optical Sensor** The HiBall-3000 tracker system is composed of two key integrated components; the HiBall Optical Sensor and the HiBall Ceiling Beacon Arrays. The HiBall Optical Sensor is composed of 6 lenses and photodiodes arranged so that each photodiode can ‘view’ infrared LEDs, in the Beacon Arrays mounted on the ceiling, through several of the 6 lenses. The assembly includes signal processing and analog-to-digital conversion circuitry. The total weight is about 6 ounces, making it light enough to comfortably mount on a headmounted display or hand-held device. By locating the sensors on the person or object being tracked — *inside-out tracking* — sensitivity around the working area is increased and the tracker area scales almost without limit. An entire lab, movie set, or assembly area can be tracked. The HiBall can also be mounted on a small probe or stylus, enabling extremely accurate measurements of individual objects within a large space. For example, this can be used for very rapid measurement of actual television or movie sets or other real-world objects to be combined with virtual scenes. No other device can provide comparable speed and accuracy over a wide area. 3rdTech at 1. **HiBall Beacon Array Modules**

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	The infrared LEDs 'seen' by the HiBall Sensor are embedded in a series of ceiling mounted strips forming a 2D Beacon Array - 8 LEDs per strip; 6 strips per Beacon Array Module (BAM). These strips are designed to slip easily into a typical 'drop ceiling' with no changes required in panels, lights, vents, etc. - the more BAMs employed, the greater the range of the tracker. The arrays are highly modular — available in configurations covering as little as 64 square feet (8' x 8') or more than 1,600 square feet (40' x 40'). And no special adjustments are required to the ceiling structure — the system's precision is unaffected by typical variations in ceiling height. The HiBall Sensor and the Beacon Arrays are synchronized by a Ceiling- HiBall Interface Board (CIB), part of the system's integrated PC, which enables extremely high rates of LED 'sightings'— approximately 2,000 per second. This results in a tracker update rate of 2,000 Hz — several times faster than other commercially available wide-area trackers. Faster updates means lower latency and more accurate tracking - even with rapid movements. **AutoCalibration** The system makes use of a *single constraint at a time* (SCAAT) algorithm to compute the location and orientation of the HiBall Sensor at every LED sighting. In addition, the system incorporates *auto-calibration* — tuning the modeled location of individual LEDs on every update. This accommodates typical shifts and movements in the ceiling tiles and BAMs without loss of accuracy or performance. **Applications** The range and performance of the HiBall-3000 Tracker open up new possibilities for large-scale virtual reality such as exploring full-size architectural designs or engineering prototypes. Its precision enables largescale augmented reality for applications in medicine, training and entertainment where accurate correspondence between physical reality and the virtual world are critical. **Proven Results** Developed in the Computer Science Department of the University of North Carolina at Chapel Hill (see www.cs.unc.edu/~tracker), the original HiBall tracker has been in use since 1997 and has consistently exceeded performance expectations. 3rdTech at 1.

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	HiBall-3000 Specifications and Performance **Hardware Components** HiBall Optical Sensor(s) — 2 7/8" tall, 2 1/8" diam, 6 OZ Beacon Array Module (BAM) — Six 2' x 1" x 7/8" strips, 8 sq. ft. PC-based Controller — Includes CIB I/F Board Connections — Ethernet (VRPN), Serial (Standard Library Interface) **Software Components** VR Peripheral Network (VRPN) support — Integrate system with other VR devices Standard Library Interface — Compatible with existing systems HBT Toolkit — Tools for set up, configuration and testing HBT Library — Low-level system access Output — Stream or point mode; XYZ coordinates; Quaternion, Euler angles or rotation matrices 3rdTech at 2. **HiBall-3000 Wide-Area Tracker Features** • Very Wide Area — Scalable to over 1,600 sq.ft. • High Precision — Ideal for augmented reality apps and rapid scene digitizing • High-update, low latency — Solid, high-speed tracking; no "swimming" • Small, light sensor — Head or stylus mountable • Easy installation — Installs in standard drop ceilings; requires no room modifications • Multiple sensors — Multiple participants or head plus hand tracking • No metal/sound interference — Requires no modification of the environment • Accurate every-where — Consistent tracking near edges of space as well as in center 3rdTech at 2. **3. SYSTEM OVERVIEW** The HiBall Tracking System consists of three main components (Figure 6). An outward-looking sensing unit we call the *HiBall* is fixed to each user to be tracked. The HiBall unit observes a subsystem of fixed-location infrared LEDs we call the *Ceiling* 1. Communication and synchronization between the host computer and these subsystems is coordinated by the *Ceiling-HiBall Interface Board* (CIB). In Section 4 we describe these components in more detail. Each HiBall observes LEDs through multiple sensor-lens *views* that are distributed

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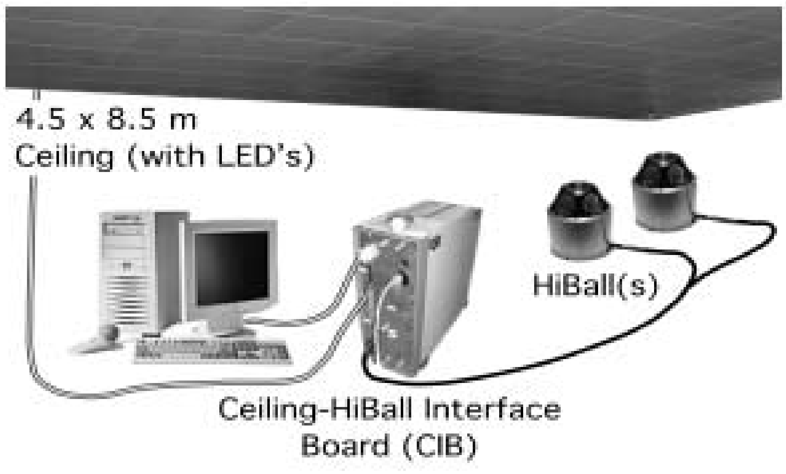
	over a large solid angle. LEDs are sequentially flashed (one at a time) such that they are seen via a diverse set of views for each HiBall. Initial *acquisition* is performed using a brute force search through LED space, but once initial lock is made, the selection of LEDs to flash is tailored to the views of the active HiBall units. Pose estimates are maintained using a Kalman-filter-based prediction-correction approach known as *single-constraint-at-a-time* or SCAAT tracking. This technique has been extended to provide self-calibration of the Ceiling, concurrent with HiBall tracking. In Section 5 we describe the methods we employ, including the initial acquisition process and the SCAAT approach to pose estimation, with the *autocalibration* extension. Welch HiBall at 6.  **Figure 6** Welch HiBall at Fig. 6. **4.3 The Ceiling-HiBall Interface Board** The Ceiling-HiBall Interface Board or CIB (Figure 11) provides communication and synchronization between a host personal computer, the HiBall (Section 4.1), and the Ceiling (Section 4.2). The CIB has four Ceiling ports allowing interleaving of ceiling panels for up to four simultaneous LED flashes and/or higher Ceiling bandwidth. (The Ceiling bandwidth is inherently limited by LED power restrictions as described in Section 4.2, but this can be increased by spatially multiplexing the Ceiling panels.) The CIB has two tether interfaces that can communicate with up to four daisy-chained HiBall units. The full-duplex communication with the HiBall units

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	uses a modulation scheme (BPSK) allowing future wireless operation. The interface from the CIB to the host PC is the stable IEEE1284C extended parallel port (EPP) standard. The CIB comprises analog drive and receive components as well as digital logic components. The digital components implement store and forward in both directions and synchronize the timing of the LED "on" interval within the HiBall dark-light-dark intervals (Section 5.2). The protocol supports full-duplex flow control. The data are arranged into packets that incorporate error detection. Welch HiBall at 8-9. **4. SYSTEM COMPONENTS** **4.1 The HiBall** The original electro-optical tracker (Figure 3, bottom) used independently housed lateral effect photo-diode units (LEPDs) attached to a light-weight tubular framework. As it turns out, the mechanical framework would flex (distort) during use, contributing to estimation errors. In part to address this problem the HiBall sensor unit was designed as a single rigid hollow ball having dodecahedral symmetry, with lenses in the upper six faces and LEPD on the insides of the opposing six lower faces (Figure 7). This immediately gives six primary "camera" *views* uniformly spaced by 57 degrees. The views efficiently share the same internal air space, and are rigid with respect to each other. In addition, light entering any lens sufficiently off axis can be seen by a neighboring LEPD, giving rise to five secondary views through the top or central lens, and three secondary views through the five other lenses. Overall, this provides 26 fields of view which are used to sense widely separated groups of LEDs in the environment. While the extra views complicate the initialization of the Kalman filter as described in Section 5.5, they turn out to be of great benefit during steady-state tracking by effectively increasing the overall HiBall field of view without sacrificing optical sensor resolution. The lenses are simple plano-convex fixed-focus lenses. Infrared (IR) filtering is provided by fabricating the lenses themselves from RG-780 Schott glass filter material which is opaque to better than 0.001% for all visible wavelengths, and transmissive to better than 99% for IR wavelengths longer than 830 nm. The longwave filtering limit is provided by the DLS-4 LEPD silicon photodetector (UDT Sensors, Inc.) with peak responsivity at 950 nm but essentially blind above 1150 nm. The LEPDs themselves are not imaging devices; rather they detect the centroid of the luminous flux incident on the detector. The x-position of the centroid determines the ratio of two output currents, while the y-position determines the ratio of two other output currents. The total output current of each pair are commensurate, and proportional to the total incident flux. Consequently, focus is not an issue, so the simple fixed-focus lenses work

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	well over a range of LED distances from about half a meter to infinity. The LEPDs and associated electronic components are mounted on a custom rigid-flex printed circuit board (Figure 8). This arrangement makes efficient use of the internal HiBall volume while maintaining isolation between analog and digital circuitry, and increasing reliability by alleviating the need for inter-component mechanical connectors. Figure 9 shows the physical arrangement of the folded electronics in the HiBall. Each LEPD has four transimpedance amplifiers (shown together as one "Amp" in Figure 9), the analog outputs of which are multiplexed with those of the other LEPDs, then sampled, held, and converted by four 16-bit Delta-Sigma analog-to-digital (A/D) converters. Multiple samples are integrated via an accumulator. The digitized LEPD data are organized into packets for communication back to the CIB. The packets also contain information to assist in error-detection. The communication protocol is simple, and while presently implemented by wire, the modulation scheme is amenable to a wireless implementation. The present wired implementation allows multiple HiBall units to be daisy-chained so a single cable can support a user with multiple HiBall units. Welch HiBall at 6-7. **1.3 The HiBall Tracking System** In this article we describe a new and vastly improved version of the 1991 system. We call the new system the *HiBall Tracking System*. Thanks to significant improvements in hardware and software this HiBall system offers unprecedented speed, resolution, accuracy, robustness, and flexibility. The bulky and heavy sensors and backpack of the previous system have been replaced by a small *HiBall* unit (Figure 4, bottom). In addition, the precisely machined LED ceiling panels of the previous system have been replaced by looser-tolerance panels that are relatively inexpensive to make and simple to install (Figure 4, top; Figure 10). Finally, we are using an unusual Kalman-filter-based algorithm that generates very accurate pose estimates at a high rate with low latency, and simultaneously self-calibrates the system. As a result of these improvements the HiBall Tracking System can generate over 2000 pose estimates per second, with less than one millisecond of latency, better than 0.5 millimeters and 0.03 degrees of absolute error and noise, everywhere in a 4.5 by 8.5 meter room (with over two meters of height variation). The area can be expanded by adding more panels, or by using checkerboard configurations which spread panels over a larger area. The weight of the user-worn HiBall is about 300 grams, making it lighter than one optical sensor in the 1991 system. Multiple HiBall units can be daisy chained together for head or hand tracking, pose-aware input devices, or precise 3D point. Welch HiBall at 4.

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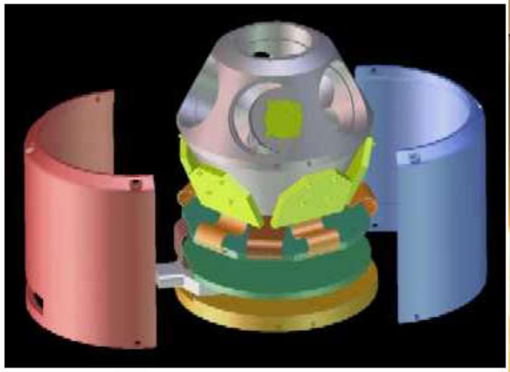
CLAIM 6	HiBall
	The HiBall tracking system resolves linear motion of less than 0.2mm and angular motions under 0.03 degrees without the distortion seen in magnetic trackers. The update rate is greater than 1500 Hz and latency is about 1ms. To our knowledge, this was the first and remains the only demonstrated scalable tracking system for HMDs. UNC HiBall Tracker at 1. **The HiBall** The HiBall is a cluster of 6 lenses and 6 photodiodes arranged so that each photodiodes can view LEDs through several of the 6 lenses, providing 26 view frustra originating at the HiBall. The assembly will include signal processing and A/D conversion circuitry. The total weight is about 5 ounces, making it lighter than just one of the cameras in the previous generation ceiling tracker. The HiBall and the ceiling panel are synchronized by a custom interface board which allows very high rate of LED sightings. The hardware alone can perform more than 3,000 sightings per second, while the whole system tracks using about 1,500. UNC HiBall Tracker at 1. **The Hiball** (Shown without lenses)   UNC HiBall Tracker at 2. **The SCAAT algorithm**

CLAIM 6	HiBall
	The UNC HiBall Tracker relies on the SCAAT (Single Constraint At A Time) algorithm to compute the user's position and orientation from the individual sightings the HiBall makes of LEDs on the ceiling panels. The algorithm makes innovative use of an Extended Kalman Filter to provide position and orientation updates after each individual LED sighting, rather than after a group of several sightings as in the previous generation of UNC ceiling tracker. In addition, SCAAT improves on previously developed auto calibration techniques to allow on-line calibration as described below. For more information see Greg Welch's SCAAT page which includes links to Greg Welch and Gary Bishop's 1997 SIGGRAPH paper on SCAAT. UNC HiBall Tracker at 2. **Autocalibration** The current ceiling's lower cost design was made possible by an auto calibration process described in Gottschalk93. The SCAAT algorithm improves on this by allowing auto calibration, tuning the actual LED positions, to be performed while the system is tracking. This accommodates shifts in the tiles and LEDs which can occur during normal use. In addition this technique opens possibilities for even less initial knowledge of LED placement than the current ceiling provides. As a test and demonstration of the autocalibration abilities of SCAAT, we have intentionally raised ceiling panels from their correct position. Here Dr. Gary Bishop is shown making the adjustments. The system was given only the initial flat LED positions, but after less than ten minutes of use (successfully tracking with the misplaced panels), SCAAT had accurately adjusted its knowledge of the LED positions through displacements more than 5cm. The above visualization shows the final measured LED positions. UNC HiBall Tracker at 2-3.

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	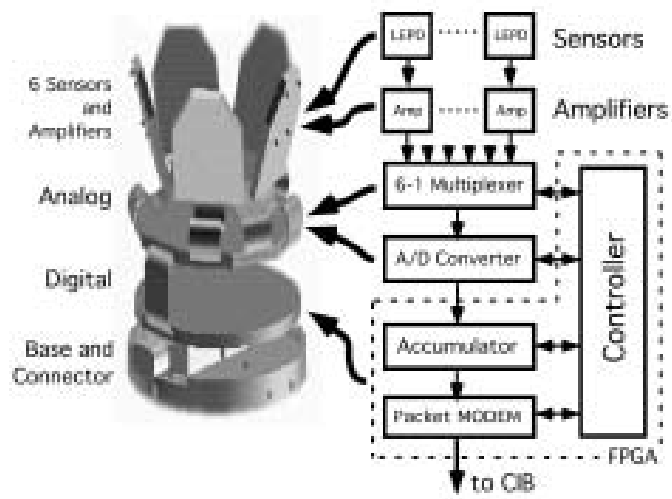 **Figure 9** Welch HiBall at Fig. 9. **4.2 The Ceiling** As presently implemented, the infrared LEDs are packaged in 61 centimeter square *panels*, to fit a standard false ceiling grid (Figure 10, top). Each panel uses five printed circuit boards: a main controller board and four identical transverse-mounted *strips* (bottom). Each strip is populated with eight LEDs for a total of 32 LEDs per panel. We mount the assembly on top of a metal panel such that the LEDs protrude through 32 corresponding holes. The design results in a Ceiling with a rectangular LED pattern with periods of 7.6 and 15.2 centimeters. This spacing is used for the initial estimates of the LED positions in the lab, then during normal operation the SCAAT algorithm continually refines the LED position estimates (Section 5.4). The SCAAT *autocalibration* not only relaxes design and installation constraints, but provides greater precision in the face of initial and ongoing uncertainty in the Ceiling structure. We currently have enough panels to cover an area approximately 5.5 by 8.5 meters with a total of approximately 3,000 LEDs. 1 The panels are daisy-chained to each other, and panel selection encoding is position (rather than device) dependent. Operational commands are presented to the first panel of the daisy chain. At each panel, if the panel select code is zero the controller decodes and executes the operation; else it decrements the panel select code and passes it along to the next panel (controller). Upon decoding, a particular LED is selected and the LED is energized. The LED brightness (power) is selectable for

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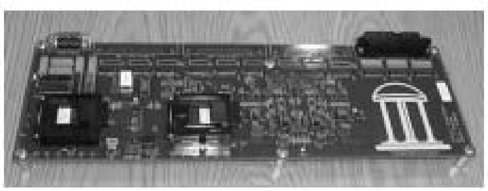
CLAIM 6	HiBall
	automatic gain control as described in Section 5.2. We currently use Siemens SFH-487P GaAs LEDs which provide both a wide angle radiation pattern and high peak power, emitting at a center wavelength of 880 nm in the near IR. These devices can be pulsed up to 2.0 Amps for a maximum duration of 200 with a 1:50 (on:off) duty cycle. While the current Ceiling architecture allows flashing of only one LED at a time, LEDs may be flashed in any sequence. As such no single LED can be flashed too long or too frequently. We include both hardware and software protection to prevent this. **4.3 The Ceiling-HiBall Interface Board** The Ceiling-HiBall Interface Board or CIB (Figure 11) provides communication and synchronization between a host personal computer, the HiBall (Section 4.1), and the Ceiling (Section 4.2). The CIB has four Ceiling ports allowing interleaving of ceiling panels for up to four simultaneous LED flashes and/or higher Ceiling bandwidth. (The Ceiling bandwidth is inherently limited by LED power restrictions as described in Section 4.2, but this can be increased by spatially multiplexing the Ceiling panels.) The CIB has two tether interfaces that can communicate with up to four daisy-chained HiBall units. The full-duplex communication with the HiBall units uses a modulation scheme (BPSK) allowing future wireless operation. The interface from the CIB to the host PC is the stable IEEE1284C extended parallel port (EPP) standard. The CIB comprises analog drive and receive components as well as digital logic components. The digital components implement store and forward in both directions and synchronize the timing of the LED "on" interval within the HiBall dark-light-dark intervals (Section 5.2). The protocol supports full-duplex flow control. The data are arranged into packets that incorporate error detection. Welch HiBall at 8-9.  Figure 11 Welch HiBall at Fig. 11. **The SCAAT algorithm**

CLAIM 6	HiBall
	The UNC HiBall Tracker relies on the SCAAT (Single Constraint At A Time) algorithm to compute the user's position and orientation from the individual sightings the HiBall makes of LEDs on the ceiling panels. The algorithm makes innovative use of an Extended Kalman Filter to provide position and orientation updates after each individual LED sighting, rather than after a group of several sightings as in the previous generation of UNC ceiling tracker. In addition, SCAAT improves on previously developed auto calibration techniques to allow on-line calibration as described below. For more information see Greg Welch's SCAAT page which includes links to Greg Welch and Gary Bishop's 1997 SIGGRAPH paper on SCAAT. UNC HiBall Tracker at 2. **Autocalibration** The current ceiling's lower cost design was made possible by an auto calibration process described in Gottschalk93. The SCAAT algorithm improves on this by allowing auto calibration, tuning the actual LED positions, to be performed while the system is tracking. This accommodates shifts in the tiles and LEDs which can occur during normal use. In addition this technique opens possibilities for even less initial knowledge of LED placement than the current ceiling provides. As a test and demonstration of the autocalibration abilities of SCAAT, we have intentionally raised ceiling panels from their correct position. Here Dr. Gary Bishop is shown making the adjustments. The system was given only the initial flat LED positions, but after less than ten minutes of use (successfully tracking with the misplaced panels), SCAAT had accurately adjusted its knowledge of the LED positions through displacements more than 5cm. The above visualization shows the final measured LED positions. UNC HiBall Tracker at 2-3. **6.2.2 Complete System Simulations.** To produce realistic data for developing and tuning our algorithms we collected several motion paths *(*sequences of pose estimates) from our first generation electro-optical tracker (Figure 3) at its 70 Hz maximum report rate. These paths were recorded from both naive users visiting our monthly "demo days" and from experienced users in our labs. In the same fashion as we had done for (Azuma & Bishop, 1994a) we filtered the raw path data with a non-causal zero-phase-shift low-pass filter to eliminate energy above 2 Hz. The output of the low-pass filtering was then re-sampled at whatever rate we wanted to run the simulated tracker, usually 1000 Hz. For the purposes of our simulations we considered these resampled paths to be the "truth"—a perfect representation of a user's motion. Tracking error was determined by comparing the "true" path to the estimated path produced by the tracker. The simulator reads camera models describing the 26 views, the sensor noise parameters, the LED positions and their expected error, and the motion path described above. Before beginning the simulation, the

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	LED positions are perturbed from their ideal positions by adding normally distributed error to each axis. Then, for each simulated cycle of operation, the "true" pose are updated using the input motion path. Next, a view is chosen and a visible LED within that view is selected, and the image-plane coordinates of the LED on the chosen sensor are computed using the camera model for the view and the LED as described in Section 5.3. These sensor coordinates are then perturbed based on the sensor noise model (Section 6.2.1) using the distance and angle to the LED. Now these noise corrupted sensor readings are fed to the SCAAT filter to produce an updated position estimate. The position estimate is compared to the true position to produce a scalar error metric described next. Welch HiBall at 16-17. **5.4 On-line LED Autocalibration** Along with the benefit of simplicity and speed, the SCAAT approach offers the additional capability of being able to estimate the 3D positions of the LEDs in the world concurrently with the pose of the HiBall, on line, in real time. This capability is a tremendous benefit in terms of the accuracy and noise characteristics of the estimates. Accurate LED position estimates are so important that prior to the introduction of the SCAAT approach a specialized off-line approach was developed to address the problem (Gottschalk & Hughes, 1993). The method we now use for autocalibration involves defining a distinct SCAAT Kalman filter for each LED. Specifically, for each LED we maintain a state $\bar{l}$ (estimate of the 3D position) and a 3x3 Kalman filter covariance. At the beginning of each estimation cycle we form an augmented state vector $\hat{x}$ using the appropriate LED state and the current HiBall state: $\hat{x} = [\bar{x}^T, \bar{l}^T]^T$. Similarly we augment the Kalman filter error covariance matrix with that of the LED filter. We then follow the normal steps outlined in Section 5.3, with the result being that the LED portion of the filter state and covariance is updated in accordance with the measurement residual. At the end of the cycle we extract the LED portions of the state and covariance from the augmented filter, and save them externally. The effect is that as the system is being used, it continually refines its estimates of the LED positions, thereby continually improving its estimates of the HiBall pose. Again, for additional information see (Welch, 1996; Welch & Bishop, 1997). Welch HiBall at 13. The Kalman filter requires both a model of the process dynamics, and a model of the relationship between the process state and the available measurements. In part due to the simplicity of the SCAAT approach we are able to use a simple PV (position-velocity) process model (Brown & Hwang, 1992). Consider the simple example state vector $\bar{x}(t) = [x_p(t), x_v(t)]^T$ where the first element $x_p(t)$ is the pose (position or orientation) and the second

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	element $x_v(t)$ is the corresponding velocity, i.e. $x_v(t) = \frac{d}{dt}x_p(t)$. We model the continuous change in the HiBall state with the simple differential equation $$\frac{d}{dt}\bar{x}(t) = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x_p(t) \\ x_v(t) \end{bmatrix} + \begin{bmatrix} 0 \\ \mu \end{bmatrix} u(t), \quad (1)$$ where *u(t)* is a normally-distributed white (in the frequency spectrum) scalar noise process, and the scalar μ represents the magnitude or *spectral density* of the noise. We use a similar model with a distinct noise process for each of the six pose elements. We determine the individual noise magnitudes using an off-line simulation of the system and a non-linear optimization strategy that seeks to minimize the variance between the estimated pose and a known motion path. (See Section 6.2.2.) The differential equation (1) represents a continuous integrated random walk, or an integrated *Wiener* or *Brownian-motion* process. Specifically, we model each component of the linear and angular HiBall velocities as a random walk, and then use these (assuming constant inter-measurement velocity) to estimate the HiBall pose at time $t + \delta t$ as follows: $$\bar{x}(t + \delta t) = \begin{bmatrix} 1 & \delta t \\ 0 & 1 \end{bmatrix} \bar{x}(t) \quad (2)$$ for each of the six pose elements. In addition to a relatively simple process model, the HiBall measurement model is relatively simple. For any Ceiling LED (Section 4.2) and HiBall view (Section 4.1), the 2D sensor measurement can be modeled as $$\begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} c_x / c_z \\ c_y / c_z \end{bmatrix} \quad (3)$$ where $$\begin{bmatrix} c_x \\ c_y \\ c_z \end{bmatrix} = VR^{\mathrm{T}}(\hat{l}_{xyz} - \bar{x}_{xyz}), \quad (4)$$ is the camera viewing matrix from Section 5.1, is the position of the LED in the world, is the position of the HiBall in the world, and is a rotation matrix corresponding to the orientation of the HiBall in the world. In practice we maintain the orientation of the HiBall as a combination of a global (external to the state) quaternion and a set of incremental angles as described in (Welch, 1996; Welch & Bishop, 1997).

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	Welch HiBall at 11-12. **5.2 On-Line HiBall Measurements** Upon receiving a command from the CIB (Section 4.3), which is synchronized with a CIB command to the ceiling, the HiBall selects the specified LEPD and performs three measurements, one before the LED flashes, one during the LED flash, and one after the LED flash. Known as "dark-light-dark", this technique is used to subtract out DC bias, low frequency noise, and background light from the LED signal. We then convert the measured sensor coordinates to "ideal" coordinates using the calibration tables described in Section 5.1. In addition, during run time we attempt to maximize the signal-to-noise ratio of the measurement with an automatic gain control scheme. For each LED we store a target signal strength factor. We compute the LED current and number of integrations (of successive accumulated A/D samples) by dividing this strength factor by the square of the distance to the LED, estimated from the current position estimate. After a reading we look at the strength of the actual measurement. If it is larger than expected we reduce the gain, if it is less than expected we increase the gain. The increase and decrease are implemented as on-line averages with scaling such that the gain factor decreases rapidly (to avoid overflow) and increases slowly. Finally we use the measured signal strength to estimate the noise on the signal using (Chi, 1995), and then use this as the measurement noise estimate for the Kalman filter (Section 5.3). Welch HiBall at 9-10. *See also* /hiball/src/libs/tracker and /cib, including but not limited to the following: /hiball/src/libs/tracker/hiballfilter.h /hiball/src/libs/tracker/hiballfilter.cpp /hiball/src/libs/tracker/ceiling.cpp /hiball/src/libs/tracker/ceiling.h /hiball/src/libs/tracker/tracker.h /hiball/src/libs/tracker/tracker.cpp

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	/hiball/src/libs/cib/cib.h /hiball/src/libs/cib/cib.cpp *See also* Defendants' Invalidity Contentions for further discussion.
[6.a] enumerating sensing elements available to a tracking system that includes an estimation subsystem that estimates a position or orientation of an object; and	At least under Plaintiffs' apparent infringement theory, HiBall discloses, either expressly or inherently, enumerating sensing elements available to a tracking system that includes an estimation subsystem that estimates a position or orientation of an object. In the alternative, this element would be obvious over HiBall in light of the other references disclosed in Defendants' Invalidity Contentions and/or the knowledge of one of ordinary skill in the art. *See, e.g.*: **The HiBall-3000 Optical Sensor** The HiBall-3000 tracker system is composed of two key integrated components; the HiBall Optical Sensor and the HiBall Ceiling Beacon Arrays. ***The HiBall Optical Sensor is composed of 6 lenses and photodiodes*** arranged so that each photodiode can 'view' infrared LEDs, in the Beacon Arrays mounted on the ceiling, through several of the 6 lenses. The assembly includes signal processing and analog-to-digital conversion circuitry. The total weight is about 6 ounces, making it light enough to comfortably mount on a headmounted display or hand-held device. By locating the sensors on the person or object being tracked — *inside-out tracking* — sensitivity around the working area is increased and the tracker area scales almost without limit. An entire lab, movie set, or assembly area can be tracked. The HiBall can also be mounted on a small probe or stylus, enabling extremely accurate measurements of individual objects within a large space. For example, this can be used for very rapid measurement of actual television or movie sets or other real-world objects to be combined with virtual scenes. No other device can provide comparable speed and accuracy over a wide area. 3rdTech at 1. **HiBall Beacon Array Modules** ***The infrared LEDs 'seen' by the HiBall Sensor are embedded in a series of ceiling mounted strips forming a 2D Beacon Array - 8 LEDs per strip; 6 strips per Beacon Array Module (BAM)***. These strips are designed to slip easily into a typical 'drop ceiling' with no changes required in panels, lights, vents, etc. - the more BAMs employed, the greater the range of the tracker. The arrays are highly modular — available in configurations covering as little

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	as 64 square feet (8' x 8') or more than 1,600 square feet (40' x 40'). And no special adjustments are required to the ceiling structure — the system's precision is unaffected by typical variations in ceiling height. The HiBall Sensor and the Beacon Arrays are synchronized by a Ceiling- HiBall Interface Board (CIB), part of the system's integrated PC, which enables extremely high rates of LED 'sightings'— approximately 2,000 per second. This results in a tracker update rate of 2,000 Hz — several times faster than other commercially available wide-area trackers. Faster updates means lower latency and more accurate tracking - even with rapid movements. **AutoCalibration** The system makes use of a *single constraint at a time* (SCAAT) algorithm to compute the location and orientation of the HiBall Sensor at every LED sighting. In addition, the system incorporates *auto-calibration* — tuning the modeled location of individual LEDs on every update. This accommodates typical shifts and movements in the ceiling tiles and BAMs without loss of accuracy or performance. **Applications** The range and performance of the HiBall-3000 Tracker open up new possibilities for large-scale virtual reality such as exploring full-size architectural designs or engineering prototypes. Its precision enables largescale augmented reality for applications in medicine, training and entertainment where accurate correspondence between physical reality and the virtual world are critical. **Proven Results** Developed in the Computer Science Department of the University of North Carolina at Chapel Hill (see www.cs.unc.edu/~tracker), the original HiBall tracker has been in use since 1997 and has consistently exceeded performance expectations. 3rdTech at 1. **3. SYSTEM OVERVIEW** The HiBall Tracking System consists of three main components (Figure 6). An outward-looking sensing unit we call the *HiBall* is fixed to each user to be tracked. The HiBall unit observes a subsystem of fixed-location infrared LEDs we call the *Ceiling* 1. Communication and synchronization between the host computer and these subsystems is coordinated by the *Ceiling-HiBall Interface Board* (CIB). In Section 4 we describe these components in more detail. Each HiBall observes LEDs through multiple sensor-lens *views* that are distributed over a large solid angle. LEDs are sequentially flashed (one at a time) such that they are seen via a diverse set of views for each HiBall. Initial *acquisition* is performed using a brute force search through LED space, but once initial lock is made, the selection of LEDs to flash is tailored to the views of the active HiBall units. Pose estimates are maintained using a Kalman-filter-based prediction-correction approach known as *single-constraint-at-a-time* or SCAAT tracking. This technique has been extended to provide self-calibration of the Ceiling,

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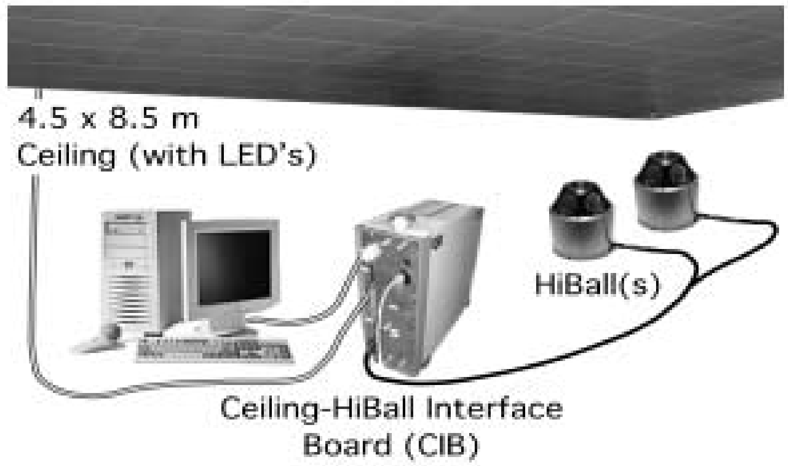
	concurrent with HiBall tracking. In Section 5 we describe the methods we employ, including the initial acquisition process and the SCAAT approach to pose estimation, with the *autocalibration* extension. Welch HiBall at 6.  **Figure 6** Welch HiBall at Fig. 6. **4.3 The Ceiling-HiBall Interface Board** The Ceiling-HiBall Interface Board or CIB (Figure 11) provides communication and synchronization between a host personal computer, the HiBall (Section 4.1), and the Ceiling (Section 4.2). The CIB has four Ceiling ports allowing interleaving of ceiling panels for up to four simultaneous LED flashes and/or higher Ceiling bandwidth. (The Ceiling bandwidth is inherently limited by LED power restrictions as described in Section 4.2, but this can be increased by spatially multiplexing the Ceiling panels.) The CIB has two tether interfaces that can communicate with up to four daisy-chained HiBall units. The full-duplex communication with the HiBall units uses a modulation scheme (BPSK) allowing future wireless operation. The interface from the CIB to the host PC is the stable IEEE1284C extended parallel port (EPP) standard. The CIB comprises analog drive and receive components as well as digital logic components. The digital components implement store and forward in both directions and synchronize the timing of the LED "on" interval within the HiBall dark-light-dark intervals

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	(Section 5.2). The protocol supports full-duplex flow control. The data are arranged into packets that incorporate error detection. Welch HiBall at 8-9. **4. SYSTEM COMPONENTS** **4.1 The HiBall** The original electro-optical tracker (Figure 3, bottom) used independently housed lateral effect photo-diode units (LEPDs) attached to a light-weight tubular framework. As it turns out, the mechanical framework would flex (distort) during use, contributing to estimation errors. In part to address this problem the HiBall sensor unit was designed as a single rigid hollow ball having dodecahedral symmetry, with lenses in the upper six faces and LEPD on the insides of the opposing six lower faces (Figure 7). This immediately gives six primary “camera” *views* uniformly spaced by 57 degrees. The views efficiently share the same internal air space, and are rigid with respect to each other. In addition, light entering any lens sufficiently off axis can be seen by a neighboring LEPD, giving rise to five secondary views through the top or central lens, and three secondary views through the five other lenses. Overall, this provides 26 fields of view which are used to sense widely separated groups of LEDs in the environment. While the extra views complicate the initialization of the Kalman filter as described in Section 5.5, they turn out to be of great benefit during steady-state tracking by effectively increasing the overall HiBall field of view without sacrificing optical sensor resolution. The lenses are simple plano-convex fixed-focus lenses. Infrared (IR) filtering is provided by fabricating the lenses themselves from RG-780 Schott glass filter material which is opaque to better than 0.001% for all visible wavelengths, and transmissive to better than 99% for IR wavelengths longer than 830 nm. The longwave filtering limit is provided by the DLS-4 LEPD silicon photodetector (UDT Sensors, Inc.) with peak responsivity at 950 nm but essentially blind above 1150 nm. The LEPDs themselves are not imaging devices; rather they detect the centroid of the luminous flux incident on the detector. The x-position of the centroid determines the ratio of two output currents, while the y-position determines the ratio of two other output currents. The total output current of each pair are commensurate, and proportional to the total incident flux. Consequently, focus is not an issue, so the simple fixed-focus lenses work well over a range of LED distances from about half a meter to infinity. The LEPDs and associated electronic components are mounted on a custom rigid-flex printed circuit board (Figure 8). This arrangement makes efficient use of the internal HiBall volume while maintaining isolation between analog and digital circuitry, and increasing reliability by alleviating the need for inter-component mechanical connectors.

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	Figure 9 shows the physical arrangement of the folded electronics in the HiBall. Each LEPD has four transimpedance amplifiers (shown together as one "Amp" in Figure 9), the analog outputs of which are multiplexed with those of the other LEPDs, then sampled, held, and converted by four 16-bit Delta-Sigma analog-to-digital (A/D) converters. Multiple samples are integrated via an accumulator. The digitized LEPD data are organized into packets for communication back to the CIB. The packets also contain information to assist in error-detection. The communication protocol is simple, and while presently implemented by wire, the modulation scheme is amenable to a wireless implementation. The present wired implementation allows multiple HiBall units to be daisy-chained so a single cable can support a user with multiple HiBall units. Welch HiBall at 6-7. **1.3 The HiBall Tracking System** In this article we describe a new and vastly improved version of the 1991 system. We call the new system the *HiBall Tracking System*. Thanks to significant improvements in hardware and software this HiBall system offers unprecedented speed, resolution, accuracy, robustness, and flexibility. The bulky and heavy sensors and backpack of the previous system have been replaced by a small *HiBall* unit (Figure 4, bottom). In addition, the precisely machined LED ceiling panels of the previous system have been replaced by looser-tolerance panels that are relatively inexpensive to make and simple to install (Figure 4, top; Figure 10). Finally, we are using an unusual Kalman-filter-based algorithm that generates very accurate pose estimates at a high rate with low latency, and simultaneously self-calibrates the system. As a result of these improvements the HiBall Tracking System can generate over 2000 pose estimates per second, with less than one millisecond of latency, better than 0.5 millimeters and 0.03 degrees of absolute error and noise, everywhere in a 4.5 by 8.5 meter room (with over two meters of height variation). The area can be expanded by adding more panels, or by using checkerboard configurations which spread panels over a larger area. The weight of the user-worn HiBall is about 300 grams, making it lighter than one optical sensor in the 1991 system. Multiple HiBall units can be daisy chained together for head or hand tracking, pose-aware input devices, or precise 3D point. Welch HiBall at 4. The HiBall tracking system resolves linear motion of less than 0.2mm and angular motions under 0.03 degrees without the distortion seen in magnetic trackers. The update rate is greater than 1500 Hz and latency is about

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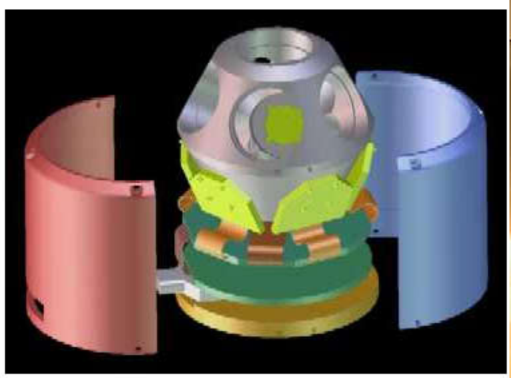
	1ms. To our knowledge, this was the first and remains the only demonstrated scalable tracking system for HMDs. UNC HiBall Tracker at 1. **The HiBall** The HiBall is a cluster of 6 lenses and 6 photodiodes arranged so that each photodiodes can view LEDs through several of the 6 lenses, providing 26 view frustra originating at the HiBall. The assembly will include signal processing and A/D conversion circuitry. The total weight is about 5 ounces, making it lighter than just one of the cameras in the previous generation ceiling tracker. The HiBall and the ceiling panel are synchronized by a custom interface board which allows very high rate of LED sightings. The hardware alone can perform more than 3,000 sightings per second, while the whole system tracks using about 1,500. UNC HiBall Tracker at 1. **The Hiball** (Shown without lenses)   UNC HiBall Tracker at 2. **The SCAAT algorithm** The UNC HiBall Tracker relies on the SCAAT (Single Constraint At A Time) algorithm to compute the user's position and orientation from the individual sightings the HiBall makes of LEDs on the ceiling panels. The

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	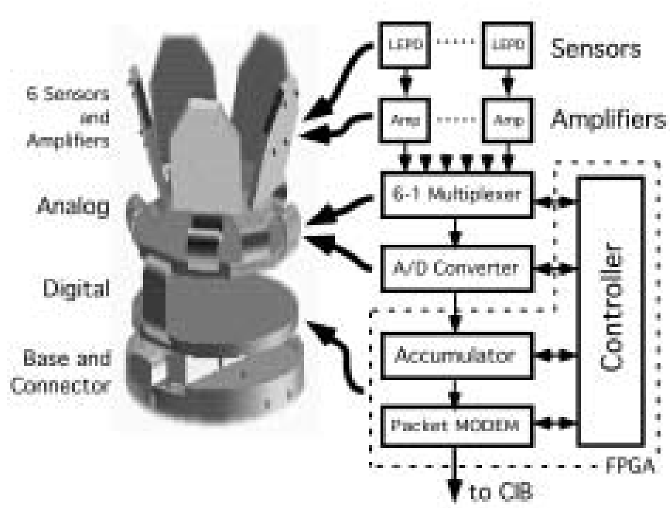 **Figure 9** Welch HiBall at Fig. 9. **4.2 The Ceiling** As presently implemented, the infrared LEDs are packaged in 61 centimeter square *panels*, to fit a standard false ceiling grid (Figure 10, top). Each panel uses five printed circuit boards: a main controller board and four identical transverse-mounted *strips* (bottom). Each strip is populated with eight LEDs for a total of 32 LEDs per panel. We mount the assembly on top of a metal panel such that the LEDs protrude through 32 corresponding holes. The design results in a Ceiling with a rectangular LED pattern with periods of 7.6 and 15.2 centimeters. This spacing is used for the initial estimates of the LED positions in the lab, then during normal operation the SCAAT algorithm continually refines the LED position estimates (Section 5.4). The SCAAT *autocalibration* not only relaxes design and installation constraints, but provides greater precision in the face of initial and ongoing uncertainty in the Ceiling structure. We currently have enough panels to cover an area approximately 5.5 by 8.5 meters with a total of approximately 3,000 LEDs. 1 The panels are daisy-chained to each other, and panel selection encoding is position (rather than device) dependent. Operational commands are presented to the first panel of the daisy chain. At each panel, if the panel select code is zero the controller decodes and executes the operation; else it decrements the panel select code and passes it along to the next panel (controller). Upon decoding, a particular LED is selected and the LED is energized. The LED brightness (power) is selectable for

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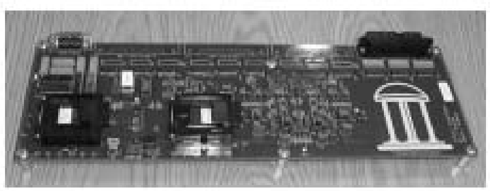
	automatic gain control as described in Section 5.2. We currently use Siemens SFH-487P GaAs LEDs which provide both a wide angle radiation pattern and high peak power, emitting at a center wavelength of 880 nm in the near IR. These devices can be pulsed up to 2.0 Amps for a maximum duration of 200 with a 1:50 (on:off) duty cycle. While the current Ceiling architecture allows flashing of only one LED at a time, LEDs may be flashed in any sequence. As such no single LED can be flashed too long or too frequently. We include both hardware and software protection to prevent this. **4.3 The Ceiling-HiBall Interface Board** The Ceiling-HiBall Interface Board or CIB (Figure 11) provides communication and synchronization between a host personal computer, the HiBall (Section 4.1), and the Ceiling (Section 4.2). The CIB has four Ceiling ports allowing interleaving of ceiling panels for up to four simultaneous LED flashes and/or higher Ceiling bandwidth. (The Ceiling bandwidth is inherently limited by LED power restrictions as described in Section 4.2, but this can be increased by spatially multiplexing the Ceiling panels.) The CIB has two tether interfaces that can communicate with up to four daisy-chained HiBall units. The full-duplex communication with the HiBall units uses a modulation scheme (BPSK) allowing future wireless operation. The interface from the CIB to the host PC is the stable IEEE1284C extended parallel port (EPP) standard. The CIB comprises analog drive and receive components as well as digital logic components. The digital components implement store and forward in both directions and synchronize the timing of the LED "on" interval within the HiBall dark-light-dark intervals (Section 5.2). The protocol supports full-duplex flow control. The data are arranged into packets that incorporate error detection. Welch HiBall at 8-9.  Figure 11 Welch HiBall at Fig. 11. **The SCAAT algorithm**

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	LED positions are perturbed from their ideal positions by adding normally distributed error to each axis. Then, for each simulated cycle of operation, the "true" pose are updated using the input motion path. Next, a view is chosen and a visible LED within that view is selected, and the image-plane coordinates of the LED on the chosen sensor are computed using the camera model for the view and the LED as described in Section 5.3. These sensor coordinates are then perturbed based on the sensor noise model (Section 6.2.1) using the distance and angle to the LED. Now these noise corrupted sensor readings are fed to the SCAAT filter to produce an updated position estimate. The position estimate is compared to the true position to produce a scalar error metric described next. Welch HiBall at 16-17. **5.4 On-line LED Autocalibration** Along with the benefit of simplicity and speed, the SCAAT approach offers the additional capability of being able to estimate the 3D positions of the LEDs in the world concurrently with the pose of the HiBall, on line, in real time. This capability is a tremendous benefit in terms of the accuracy and noise characteristics of the estimates. Accurate LED position estimates are so important that prior to the introduction of the SCAAT approach a specialized off-line approach was developed to address the problem (Gottschalk & Hughes, 1993). The method we now use for autocalibration involves defining a distinct SCAAT Kalman filter for each LED. Specifically, for each LED we maintain a state $\bar{l}$ (estimate of the 3D position) and a 3x3 Kalman filter covariance. At the beginning of each estimation cycle we form an augmented state vector $\hat{x}$ using the appropriate LED state and the current HiBall state: $\hat{x} = [\bar{x}^{\mathrm{T}}, \bar{l}^{\mathrm{T}}]^{\mathrm{T}}$. Similarly we augment the Kalman filter error covariance matrix with that of the LED filter. We then follow the normal steps outlined in Section 5.3, with the result being that the LED portion of the filter state and covariance is updated in accordance with the measurement residual. At the end of the cycle we extract the LED portions of the state and covariance from the augmented filter, and save them externally. The effect is that as the system is being used, it continually refines its estimates of the LED positions, thereby continually improving its estimates of the HiBall pose. Again, for additional information see (Welch, 1996; Welch & Bishop, 1997). Welch HiBall at 13. The Kalman filter requires both a model of the process dynamics, and a model of the relationship between the process state and the available measurements. In part due to the simplicity of the SCAAT approach we are able to use a simple PV (position-velocity) process model (Brown & Hwang, 1992). Consider the simple example state vector $\bar{x}(t) = [x_p(t), x_v(t)]^{\mathrm{T}}$ where the first element $x_p(t)$ is the pose (position or orientation) and the second

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	element $x_v(t)$ is the corresponding velocity, i.e. $x_v(t) = \frac{d}{dt}x_p(t)$. We model the continuous change in the HiBall state with the simple differential equation $$\frac{d}{dt}\bar{x}(t) = \begin{bmatrix}0 & 1\\0 & 0\end{bmatrix}\begin{bmatrix}x_p(t)\\x_v(t)\end{bmatrix} + \begin{bmatrix}0\\\mu\end{bmatrix}u(t), \qquad (1)$$ where *u(t)* is a normally-distributed white (in the frequency spectrum) scalar noise process, and the scalar μ represents the magnitude or *spectral density* of the noise. We use a similar model with a distinct noise process for each of the six pose elements. We determine the individual noise magnitudes using an off-line simulation of the system and a non-linear optimization strategy that seeks to minimize the variance between the estimated pose and a known motion path. (See Section 6.2.2.) The differential equation (1) represents a continuous integrated random walk, or an integrated *Wiener* or *Brownian-motion* process. Specifically, we model each component of the linear and angular HiBall velocities as a random walk, and then use these (assuming constant inter-measurement velocity) to estimate the HiBall pose at time $t + \delta t$ as follows: $$\bar{x}(t + \delta t) = \begin{bmatrix}1 & \delta t\\0 & 1\end{bmatrix}\bar{x}(t) \qquad (2)$$ for each of the six pose elements. In addition to a relatively simple process model, the HiBall measurement model is relatively simple. For any Ceiling LED (Section 4.2) and HiBall view (Section 4.1), ***the 2D sensor*** measurement can be modeled as $$\begin{bmatrix}u\\v\end{bmatrix} = \begin{bmatrix}c_x/c_z\\c_y/c_z\end{bmatrix} \qquad (3)$$ where $$\begin{bmatrix}c_x\\c_y\\c_z\end{bmatrix} = VR^{\mathrm{T}}(\hat{l}_{xyz} - \bar{x}_{xyz}), \qquad (4)$$ is the camera viewing matrix from Section 5.1, is the position of the LED in the world, is the position of the HiBall in the world, and is a rotation matrix corresponding to the orientation of the HiBall in the world. In practice we maintain the orientation of the HiBall as a combination of a global (external to the state) quaternion and a set of incremental angles as described in (Welch, 1996; Welch & Bishop, 1997).

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	Welch HiBall at 11-12. **5.2 On-Line HiBall Measurements** Upon receiving a command from the CIB (Section 4.3), which is synchronized with a CIB command to the ceiling, the HiBall selects the specified LEPD and performs three measurements, one before the LED flashes, one during the LED flash, and one after the LED flash. Known as “dark-light-dark”, this technique is used to subtract out DC bias, low frequency noise, and background light from the LED signal. We then convert the measured sensor coordinates to “ideal” coordinates using the calibration tables described in Section 5.1. In addition, during run time we attempt to maximize the signal-to-noise ratio of the measurement with an automatic gain control scheme. For each LED we store a target signal strength factor. We compute the LED current and number of integrations (of successive accumulated A/D samples) by dividing this strength factor by the square of the distance to the LED, estimated from the current position estimate. After a reading we look at the strength of the actual measurement. If it is larger than expected we reduce the gain, if it is less than expected we increase the gain. The increase and decrease are implemented as on-line averages with scaling such that the gain factor decreases rapidly (to avoid overflow) and increases slowly. Finally we use the measured signal strength to estimate the noise on the signal using (Chi, 1995), and then use this as the measurement noise estimate for the Kalman filter (Section 5.3). Welch HiBall at 9-10. *See also* /hiball/src/libs/tracker and /cib, including but not limited to the following: /hiball/src/libs/tracker/hiballfilter.h /hiball/src/libs/tracker/hiballfilter.cpp /hiball/src/libs/tracker/ceiling.cpp /hiball/src/libs/tracker/ceiling.h /hiball/src/libs/tracker/chooser.h /hiball/src/libs/tracker/chooser.cpp

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	/hiball/src/libs/tracker/acquire.h /hiball/src/libs/tracker/acquire.cpp /hiball/src/libs/tracker/tracker.h /hiball/src/libs/tracker/tracker.cpp /hiball/src/libs/cib/hiball.h /hiball/src/libs/cib/hiball.cpp /hiball/src/libs/cib/cib.h /hiball/src/libs/cib/cib.cpp *See also* Defendants' Invalidity Contentions for further discussion.
[6.b] providing parameters specific to the enumerated sensing elements to the tracking system to enable the estimation subsystem to be configured based on the parameters specific to the enumerated sensing elements to enable the estimation subsystem to estimate the position or orientation of the object.	At least under Plaintiffs' apparent infringement theory, HiBall discloses, either expressly or inherently, providing parameters specific to the enumerated sensing elements to the tracking system to enable the estimation subsystem to be configured based on the parameters specific to the enumerated sensing elements to enable the estimation subsystem to estimate the position or orientation of the object. In the alternative, this element would be obvious over HiBall in light of the other references disclosed in Defendants' Invalidity Contentions and/or the knowledge of one of ordinary skill in the art. *See, e.g.*: **The HiBall-3000 Optical Sensor** The HiBall-3000 tracker system is composed of two key integrated components; the HiBall Optical Sensor and the HiBall Ceiling Beacon Arrays. The HiBall Optical Sensor is composed of 6 lenses and photodiodes arranged so that each photodiode can 'view' infrared LEDs, in the Beacon Arrays mounted on the ceiling, through several of the 6 lenses. The assembly includes signal processing and analog-to-digital conversion circuitry. The total weight

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	is about 6 ounces, making it light enough to comfortably mount on a headmounted display or hand-held device. By locating the sensors on the person or object being tracked — *inside-out tracking* — sensitivity around the working area is increased and the tracker area scales almost without limit. An entire lab, movie set, or assembly area can be tracked. The HiBall can also be mounted on a small probe or stylus, enabling extremely accurate measurements of individual objects within a large space. For example, this can be used for very rapid measurement of actual television or movie sets or other real-world objects to be combined with virtual scenes. No other device can provide comparable speed and accuracy over a wide area. 3rdTech at 1. **HiBall Beacon Array Modules** The infrared LEDs 'seen' by the HiBall Sensor are embedded in a series of ceiling mounted strips forming a 2D Beacon Array - 8 LEDs per strip; 6 strips per Beacon Array Module (BAM). These strips are designed to slip easily into a typical 'drop ceiling' with no changes required in panels, lights, vents, etc. - the more BAMs employed, the greater the range of the tracker. The arrays are highly modular — available in configurations covering as little as 64 square feet (8' x 8') or more than 1,600 square feet (40' x 40'). And no special adjustments are required to the ceiling structure — the system's precision is unaffected by typical variations in ceiling height. The HiBall Sensor and the Beacon Arrays are synchronized by a Ceiling- HiBall Interface Board (CIB), part of the system's integrated PC, which enables extremely high rates of LED 'sightings'— approximately 2,000 per second. This results in a tracker update rate of 2,000 Hz — several times faster than other commercially available wide-area trackers. Faster updates means lower latency and more accurate tracking - even with rapid movements. **AutoCalibration** The system makes use of a *single constraint at a time* (SCAAT) algorithm to compute the location and orientation of the HiBall Sensor at every LED sighting. In addition, ***the system incorporates auto-calibration — tuning the modeled location of individual LEDs on every update. This accommodates typical shifts and movements in the ceiling tiles and BAMs without loss of accuracy or performance.*** **Applications** The range and performance of the HiBall-3000 Tracker open up new possibilities for large-scale virtual reality such as exploring full-size architectural designs or engineering prototypes. Its precision enables largescale augmented reality for applications in medicine, training and entertainment where accurate correspondence between physical reality and the virtual world are critical. **Proven Results**

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	Developed in the Computer Science Department of the University of North Carolina at Chapel Hill (see www.cs.unc.edu/~tracker), the original HiBall tracker has been in use since 1997 and has consistently exceeded performance expectations. 3rdTech at 1. **3. SYSTEM OVERVIEW** The HiBall Tracking System consists of three main components (Figure 6). An outward-looking sensing unit we call the *HiBall* is fixed to each user to be tracked. The HiBall unit observes a subsystem of fixed-location infrared LEDs we call the *Ceiling* 1. Communication and synchronization between the host computer and these subsystems is coordinated by the *Ceiling-HiBall Interface Board* (CIB). In Section 4 we describe these components in more detail. Each HiBall observes LEDs through multiple sensor-lens *views* that are distributed over a large solid angle. LEDs are sequentially flashed (one at a time) such that they are seen via a diverse set of views for each HiBall. Initial *acquisition* is performed using a brute force search through LED space, but once initial lock is made, the selection of LEDs to flash is tailored to the views of the active HiBall units. Pose estimates are maintained using a Kalman-filter-based prediction-correction approach known as *single-constraint-at-a-time* or SCAAT tracking. This technique has been extended to provide self-calibration of the Ceiling, concurrent with HiBall tracking. In Section 5 we describe the methods we employ, including the initial acquisition process and the SCAAT approach to pose estimation, with the *autocalibration* extension. Welch HiBall at 6.

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	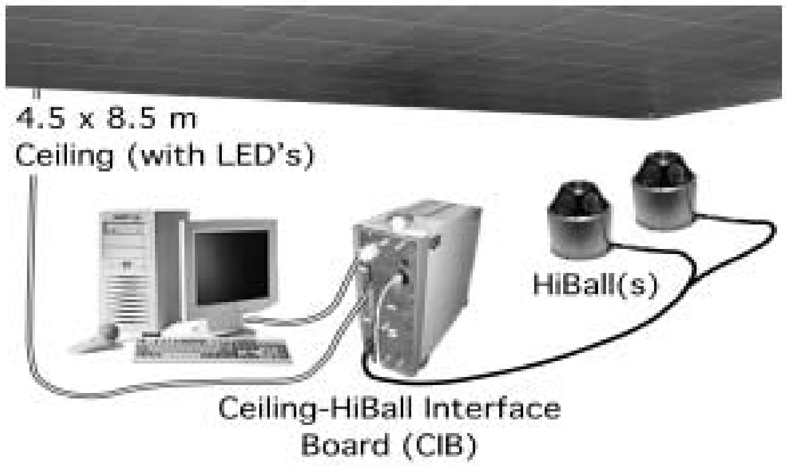 Figure 6 Welch HiBall at Fig. 6. **4.3 The Ceiling-HiBall Interface Board** The Ceiling-HiBall Interface Board or CIB (Figure 11) provides communication and synchronization between a host personal computer, the HiBall (Section 4.1), and the Ceiling (Section 4.2). The CIB has four Ceiling ports allowing interleaving of ceiling panels for up to four simultaneous LED flashes and/or higher Ceiling bandwidth. (The Ceiling bandwidth is inherently limited by LED power restrictions as described in Section 4.2, but this can be increased by spatially multiplexing the Ceiling panels.) The CIB has two tether interfaces that can communicate with up to four daisy-chained HiBall units. The full-duplex communication with the HiBall units uses a modulation scheme (BPSK) allowing future wireless operation. The interface from the CIB to the host PC is the stable IEEE1284C extended parallel port (EPP) standard. The CIB comprises analog drive and receive components as well as digital logic components. The digital components implement store and forward in both directions and synchronize the timing of the LED "on" interval within the HiBall dark-light-dark intervals (Section 5.2). The protocol supports full-duplex flow control. The data are arranged into packets that incorporate error detection. Welch HiBall at 8-9.

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	4. SYSTEM COMPONENTS **4.1 The HiBall** The original electro-optical tracker (Figure 3, bottom) used independently housed lateral effect photo-diode units (LEPDs) attached to a light-weight tubular framework. As it turns out, the mechanical framework would flex (distort) during use, contributing to estimation errors. In part to address this problem the HiBall sensor unit was designed as a single rigid hollow ball having dodecahedral symmetry, with lenses in the upper six faces and LEPD on the insides of the opposing six lower faces (Figure 7). This immediately gives six primary "camera" *views* uniformly spaced by 57 degrees. The views efficiently share the same internal air space, and are rigid with respect to each other. In addition, light entering any lens sufficiently off axis can be seen by a neighboring LEPD, giving rise to five secondary views through the top or central lens, and three secondary views through the five other lenses. Overall, this provides 26 fields of view which are used to sense widely separated groups of LEDs in the environment. While the extra views complicate the initialization of the Kalman filter as described in Section 5.5, they turn out to be of great benefit during steady-state tracking by effectively increasing the overall HiBall field of view without sacrificing optical sensor resolution. The lenses are simple plano-convex fixed-focus lenses. Infrared (IR) filtering is provided by fabricating the lenses themselves from RG-780 Schott glass filter material which is opaque to better than 0.001% for all visible wavelengths, and transmissive to better than 99% for IR wavelengths longer than 830 nm. The longwave filtering limit is provided by the DLS-4 LEPD silicon photodetector (UDT Sensors, Inc.) with peak responsivity at 950 nm but essentially blind above 1150 nm. The LEPDs themselves are not imaging devices; rather they detect the centroid of the luminous flux incident on the detector. The x-position of the centroid determines the ratio of two output currents, while the y-position determines the ratio of two other output currents. The total output current of each pair are commensurate, and proportional to the total incident flux. Consequently, focus is not an issue, so the simple fixed-focus lenses work well over a range of LED distances from about half a meter to infinity. The LEPDs and associated electronic components are mounted on a custom rigid-flex printed circuit board (Figure 8). This arrangement makes efficient use of the internal HiBall volume while maintaining isolation between analog and digital circuitry, and increasing reliability by alleviating the need for inter-component mechanical connectors. Figure 9 shows the physical arrangement of the folded electronics in the HiBall. Each LEPD has four transimpedance amplifiers (shown together as one "Amp" in Figure 9), the analog outputs of which are multiplexed with those of the other LEPDs, then sampled, held, and converted by four 16-bit Delta-Sigma

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	analog-to-digital (A/D) converters. Multiple samples are integrated via an accumulator. The digitized LEPD data are organized into packets for communication back to the CIB. The packets also contain information to assist in error-detection. The communication protocol is simple, and while presently implemented by wire, the modulation scheme is amenable to a wireless implementation. The present wired implementation allows multiple HiBall units to be daisy-chained so a single cable can support a user with multiple HiBall units. Welch HiBall at 6-7. **1.3 The HiBall Tracking System** In this article we describe a new and vastly improved version of the 1991 system. We call the new system the *HiBall Tracking System*. Thanks to significant improvements in hardware and software this HiBall system offers unprecedented speed, resolution, accuracy, robustness, and flexibility. The bulky and heavy sensors and backpack of the previous system have been replaced by a small *HiBall* unit (Figure 4, bottom). In addition, the precisely machined LED ceiling panels of the previous system have been replaced by looser-tolerance panels that are relatively inexpensive to make and simple to install (Figure 4, top; Figure 10). Finally, we are using an unusual Kalman-filter-based algorithm that generates very accurate pose estimates at a high rate with low latency, and simultaneously self-calibrates the system. As a result of these improvements the HiBall Tracking System can generate over 2000 pose estimates per second, with less than one millisecond of latency, better than 0.5 millimeters and 0.03 degrees of absolute error and noise, everywhere in a 4.5 by 8.5 meter room (with over two meters of height variation). The area can be expanded by adding more panels, or by using checkerboard configurations which spread panels over a larger area. The weight of the user-worn HiBall is about 300 grams, making it lighter than one optical sensor in the 1991 system. Multiple HiBall units can be daisy chained together for head or hand tracking, pose-aware input devices, or precise 3D point. Welch HiBall at 4. The HiBall tracking system resolves linear motion of less than 0.2mm and angular motions under 0.03 degrees without the distortion seen in magnetic trackers. The update rate is greater than 1500 Hz and latency is about 1ms. To our knowledge, this was the first and remains the only demonstrated scalable tracking system for HMDs. UNC HiBall Tracker at 1. **The HiBall**

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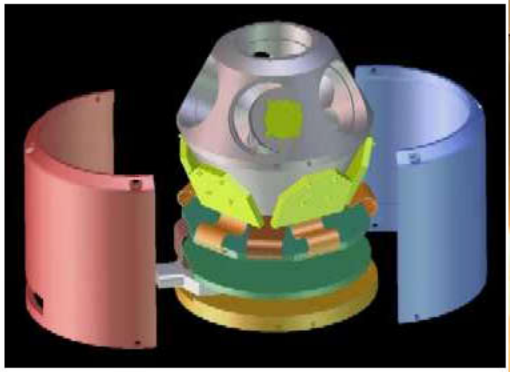
	The HiBall is a cluster of 6 lenses and 6 photodiodes arranged so that each photodiodes can view LEDs through several of the 6 lenses, providing 26 view frustra originating at the HiBall. The assembly will include signal processing and A/D conversion circuitry. The total weight is about 5 ounces, making it lighter than just one of the cameras in the previous generation ceiling tracker. The HiBall and the ceiling panel are synchronized by a custom interface board which allows very high rate of LED sightings. The hardware alone can perform more than 3,000 sightings per second, while the whole system tracks using about 1,500. UNC HiBall Tracker at 1. **The Hiball** (Shown without lenses)   UNC HiBall Tracker at 2. **The SCAAT algorithm** The UNC HiBall Tracker relies on the SCAAT (Single Constraint At A Time) algorithm to compute the user's position and orientation from the individual sightings the HiBall makes of LEDs on the ceiling panels. The algorithm makes innovative use of an Extended Kalman Filter to provide position and orientation updates after each individual LED sighting, rather than after a group of several sightings as in the previous generation of UNC ceiling tracker. In addition, SCAAT improves on previously developed auto calibration techniques to allow on-line calibration as described below. For more information see Greg Welch's SCAAT page which includes links to

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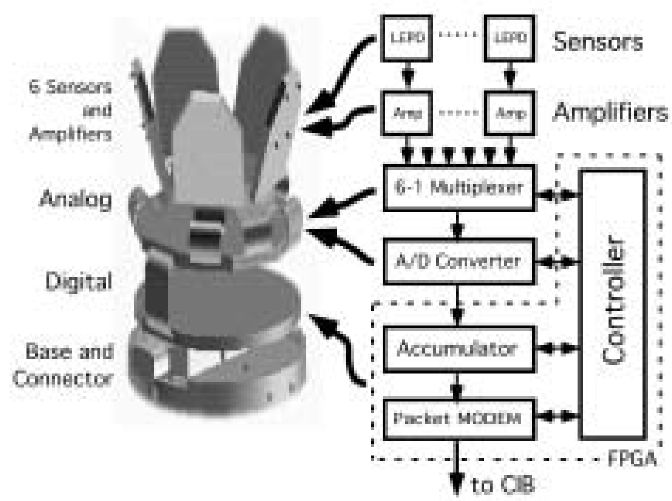
	Greg Welch and Gary Bishop's 1997 SIGGRAPH paper on SCAAT. UNC HiBall Tracker at 2. **Autocalibration** The current ceiling's lower cost design was made possible by an auto calibration process described in Gottschalk93. The SCAAT algorithm improves on this by allowing auto calibration, tuning the actual LED positions, to be performed while the system is tracking. ***This accommodates shifts in the tiles and LEDs*** which can occur during normal use. In addition this technique opens possibilities for even less initial knowledge of LED placement than the current ceiling provides. As a test and demonstration of the autocalibration abilities of SCAAT, we have intentionally r***aised ceiling panels from their correct position***. Here Dr. Gary Bishop is shown making the adjustments. The system was given only the initial flat LED positions, ***but after less than ten minutes of use (successfully tracking with the misplaced panels), SCAAT had accurately adjusted its knowledge of the LED positions through displacements more than 5cm. The above visualization shows the final measured LED positions.*** UNC HiBall Tracker at 2-3.  **Figure 9**

CLAIM 6	HiBall
	Welch HiBall at Fig. 9. **4.2 The Ceiling** As presently implemented, the infrared LEDs are packaged in 61 centimeter square *panels*, to fit a standard false ceiling grid (Figure 10, top). Each panel uses five printed circuit boards: a main controller board and four identical transverse-mounted *strips* (bottom). Each strip is populated with eight LEDs for a total of 32 LEDs per panel. We mount the assembly on top of a metal panel such that the LEDs protrude through 32 corresponding holes. The design results in a Ceiling with a rectangular LED pattern with periods of 7.6 and 15.2 centimeters. This spacing is used for the initial estimates of the LED positions in the lab, then during normal operation the SCAAT algorithm continually refines the LED position estimates (Section 5.4). The SCAAT *autocalibration* not only relaxes design and installation constraints, but provides greater precision in the face of initial and ongoing uncertainty in the Ceiling structure. We currently have enough panels to cover an area approximately 5.5 by 8.5 meters with a total of approximately 3,000 LEDs. 1 The panels are daisy-chained to each other, and panel selection encoding is position (rather than device) dependent. Operational commands are presented to the first panel of the daisy chain. At each panel, if the panel select code is zero the controller decodes and executes the operation; else it decrements the panel select code and passes it along to the next panel (controller). Upon decoding, a particular LED is selected and the LED is energized. The LED brightness (power) is selectable for *automatic gain control* as described in Section 5.2. We currently use Siemens SFH-487P GaAs LEDs which provide both a wide angle radiation pattern and high peak power, emitting at a center wavelength of 880 nm in the near IR. These devices can be pulsed up to 2.0 Amps for a maximum duration of 200 with a 1:50 (on:off) duty cycle. While the current Ceiling architecture allows flashing of only one LED at a time, LEDs may be flashed in any sequence. As such no single LED can be flashed too long or too frequently. We include both hardware and software protection to prevent this. **4.3 The Ceiling-HiBall Interface Board** The Ceiling-HiBall Interface Board or CIB (Figure 11) provides communication and synchronization between a host personal computer, the HiBall (Section 4.1), and the Ceiling (Section 4.2). The CIB has four Ceiling ports allowing interleaving of ceiling panels for up to four simultaneous LED flashes and/or higher Ceiling bandwidth. (The Ceiling bandwidth is inherently limited by LED power restrictions as described in Section 4.2, but this can be increased by spatially multiplexing the Ceiling panels.) The CIB has two tether interfaces that can communicate with up to four daisy-chained HiBall units. The full-duplex communication with the HiBall units uses a modulation scheme (BPSK) allowing future wireless operation. The interface from the CIB to the host PC is the stable IEEE1284C extended parallel port (EPP) standard. The CIB comprises analog drive and receive

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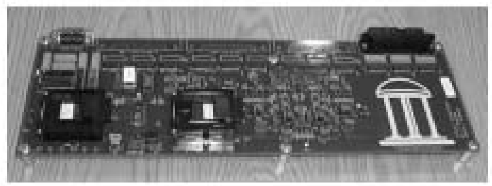
	components as well as digital logic components. The digital components implement store and forward in both directions and synchronize the timing of the LED "on" interval within the HiBall dark-light-dark intervals (Section 5.2). The protocol supports full-duplex flow control. The data are arranged into packets that incorporate error detection. Welch HiBall at 8-9.  **Figure 11** Welch HiBall at Fig. 11. **The SCAAT algorithm** The UNC HiBall Tracker relies on the SCAAT (Single Constraint At A Time) algorithm to compute the user's position and orientation from the individual sightings the HiBall makes of LEDs on the ceiling panels. The algorithm makes innovative use of an Extended Kalman Filter to provide position and orientation updates after each individual LED sighting, rather than after a group of several sightings as in the previous generation of UNC ceiling tracker. In addition, SCAAT improves on previously developed auto calibration techniques to allow on-line calibration as described below. For more information see Greg Welch's SCAAT page which includes links to Greg Welch and Gary Bishop's 1997 SIGGRAPH paper on SCAAT. UNC HiBall Tracker at 2. **Autocalibration** The current ceiling's lower cost design was made possible by an auto calibration process described in Gottschalk93. ***The SCAAT algorithm improves on this by allowing auto calibration, tuning the actual LED positions, to be performed while the system is tracking.*** This accommodates shifts in the tiles and LEDs which can occur during normal use. In addition this technique opens possibilities for even less initial knowledge of LED placement than the current ceiling provides.

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	As a test and demonstration of the autocalibration abilities of SCAAT, we have intentionally raised ceiling panels from their correct position. Here Dr. Gary Bishop is shown making the adjustments. The system was given only the initial flat LED positions, but after less than ten minutes of use (successfully tracking with the misplaced panels), SCAAT had accurately adjusted its knowledge of the LED positions through displacements more than 5cm. The above visualization shows the final measured LED positions. UNC HiBall Tracker at 2-3. **6.2.2 Complete System Simulations.** To produce realistic data for developing and tuning our algorithms we collected several motion paths *(*sequences of pose estimates) from our first generation electro-optical tracker (Figure 3) at its 70 Hz maximum report rate. These paths were recorded from both naive users visiting our monthly "demo days" and from experienced users in our labs. In the same fashion as we had done for (Azuma & Bishop, 1994a) we filtered the raw path data with a non-causal zero-phase-shift low-pass filter to eliminate energy above 2 Hz. The output of the low-pass filtering was then re-sampled at whatever rate we wanted to run the simulated tracker, usually 1000 Hz. For the purposes of our simulations we considered these resampled paths to be the "truth"—a perfect representation of a user's motion. Tracking error was determined by comparing the "true" path to the estimated path produced by the tracker. The simulator reads camera models describing the 26 views, the sensor noise parameters, the LED positions and their expected error, and the motion path described above. Before beginning the simulation, the LED positions are perturbed from their ideal positions by adding normally distributed error to each axis. Then, for each simulated cycle of operation, the "true" pose are updated using the input motion path. Next, a view is chosen and a visible LED within that view is selected, and the image-plane coordinates of the LED on the chosen sensor are computed using the camera model for the view and the LED as described in Section 5.3. These sensor coordinates are then perturbed based on the sensor noise model (Section 6.2.1) using the distance and angle to the LED. Now these noise corrupted sensor readings are fed to the SCAAT filter to produce an updated position estimate. The position estimate is compared to the true position to produce a scalar error metric described next. Welch HiBall at 16-17. **5.4 On-line LED Autocalibration** Along with the benefit of simplicity and speed, the SCAAT approach offers the additional capability of being able to estimate the 3D positions of the LEDs in the world concurrently with the pose of the HiBall, on line, in real time. This capability is a tremendous benefit in terms of the accuracy and noise characteristics of the estimates. Accurate LED position estimates are so important that prior to the introduction of the SCAAT approach a specialized off-line approach was developed to address the problem (Gottschalk & Hughes, 1993).

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	The method we now use for autocalibration involves defining a distinct SCAAT Kalman filter for each LED. Specifically, for each LED we maintain a state $\bar{l}$ (estimate of the 3D position) and a 3x3 Kalman filter covariance. At the beginning of each estimation cycle we form an augmented state vector $\hat{x}$ using the appropriate LED state and the current HiBall state: $\hat{x} = [\bar{x}^{\mathrm{T}}, \bar{l}^{\mathrm{T}}]^{\mathrm{T}}$. Similarly we augment the Kalman filter error covariance matrix with that of the LED filter. We then follow the normal steps outlined in Section 5.3, with the result being that the LED portion of the filter state and covariance is updated in accordance with the measurement residual. At the end of the cycle we extract the LED portions of the state and covariance from the augmented filter, and save them externally. The effect is that as the system is being used, it continually refines its estimates of the LED positions, thereby continually improving its estimates of the HiBall pose. Again, for additional information see (Welch, 1996; Welch & Bishop, 1997). Welch HiBall at 13. The Kalman filter requires both a model of the process dynamics, and a model of the relationship between the process state and the available measurements. In part due to the simplicity of the SCAAT approach we are able to use a simple PV (position-velocity) process model (Brown & Hwang, 1992). Consider the simple example state vector $\bar{x}(t) = [x_p(t), x_v(t)]^{\mathrm{T}}$ where the first element $x_p(t)$ is the pose (position or orientation) and the second element $x_v(t)$ is the corresponding velocity, i.e. $x_v(t) = \frac{d}{dt} x_p(t)$. We model the continuous change in the HiBall state with the simple differential equation $$\frac{d}{dt}\bar{x}(t) = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} x_p(t) \\ x_v(t) \end{bmatrix} + \begin{bmatrix} 0 \\ \mu \end{bmatrix} u(t), \qquad (1)$$ where *u(t)* is a normally-distributed white (in the frequency spectrum) scalar noise process, and the scalar μ represents the magnitude or *spectral density* of the noise. We use a similar model with a distinct noise process for each of the six pose elements. We determine the individual noise magnitudes using an off-line simulation of the system and a non-linear optimization strategy that seeks to minimize the variance between the estimated pose and a known motion path. (See Section 6.2.2.) The differential equation (1) represents a continuous integrated random walk, or an integrated *Wiener* or *Brownian-motion* process. Specifically, we model each component of the linear and angular HiBall velocities as a random walk, and then use these (assuming constant inter-measurement velocity) to estimate the HiBall pose at time $t + \delta t$ as follows:

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CLAIM 6	HiBall
	$\bar{x}(t+\delta t) = \begin{bmatrix} 1 & \delta t \\ 0 & 1 \end{bmatrix} \bar{x}(t)$ (2) for each of the six pose elements. In addition to a relatively simple process model, the HiBall measurement model is relatively simple. For any Ceiling LED (Section 4.2) and HiBall view (Section 4.1), the 2D sensor measurement can be modeled as $\begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} c_x/c_z \\ c_y/c_z \end{bmatrix}$ (3) where $\begin{bmatrix} c_x \\ c_y \\ c_z \end{bmatrix} = VR^{T}(\hat{l}_{xyz} - \bar{x}_{xyz})$, (4) is the camera viewing matrix from Section 5.1, is the position of the LED in the world, is the position of the HiBall in the world, and is a rotation matrix corresponding to the orientation of the HiBall in the world. In practice we maintain the orientation of the HiBall as a combination of a global (external to the state) quaternion and a set of incremental angles as described in (Welch, 1996; Welch & Bishop, 1997). Welch HiBall at 11-12. **5.2 On-Line HiBall Measurements** Upon receiving a command from the CIB (Section 4.3), which is synchronized with a CIB command to the ceiling, the HiBall selects the specified LEPD and performs three measurements, one before the LED flashes, one during the LED flash, and one after the LED flash. Known as “dark-light-dark”, this technique is used to subtract out DC bias, low frequency noise, and background light from the LED signal. We then convert the measured sensor coordinates to “ideal” coordinates using the calibration tables described in Section 5.1. In addition, during run time we attempt to maximize the signal-to-noise ratio of the measurement with an automatic gain control scheme. For each LED we store a target signal strength factor. We compute the LED current and number of integrations (of successive accumulated A/D samples) by dividing this strength factor by the square of the distance to the LED, estimated from the current position estimate. After a reading we look at the strength of the actual measurement. If it is larger than expected we reduce the gain, if it is less than expected we increase the gain. The increase and decrease are implemented as on-line averages with scaling such that the gain

CLAIM 6	HiBall
	factor decreases rapidly (to avoid overflow) and increases slowly. Finally we use the measured signal strength to estimate the noise on the signal using (Chi, 1995), and then use this as the measurement noise estimate for the Kalman filter (Section 5.3). Welch HiBall at 9-10. *See also* /hiball/src/libs/tracker and /cib, including but not limited to the following: /hiball/src/libs/tracker/hiballfilter.h /hiball/src/libs/tracker/hiballfilter.cpp /hiball/src/libs/tracker/tracker.h /hiball/src/libs/tracker/tracker.cpp /hiball/src/libs/cib/hiball.h /hiball/src/libs/cib/hiball.cpp *See also* Defendants' Invalidity Contentions for further discussion.

F. DEPENDENT CLAIM 8

CLAIM 8	HiBall
[8] The method of claim 6 wherein the set of sensing elements comprises at least one sensor and at least one target, the sensor making	At least under Plaintiffs' apparent infringement theory, HiBall discloses, either expressly or inherently, the method of claim 6 wherein the set of sensing elements comprises at least one sensor and at least one target, the sensor making a measurement with respect to the target. In the alternative, this element would be obvious over HiBall in light of the other references disclosed in Defendants' Invalidity Contentions and/or the knowledge of one of ordinary skill in the art. *See, e.g.*:

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CLAIM 8	HiBall
a measurement with respect to the target.	**The HiBall-3000 Optical Sensor** The HiBall-3000 tracker system is composed of two key integrated components; the HiBall Optical Sensor and the HiBall Ceiling Beacon Arrays. The HiBall Optical Sensor is composed of 6 lenses and photodiodes arranged so that each photodiode can 'view' infrared LEDs, in the Beacon Arrays mounted on the ceiling, through several of the 6 lenses. The assembly includes signal processing and analog-to-digital conversion circuitry. The total weight is about 6 ounces, making it light enough to comfortably mount on a headmounted display or hand-held device. ***By locating the sensors on the person or object being tracked — inside-out tracking — sensitivity around the working area is increased and the tracker area scales almost without limit***. An entire lab, movie set, or assembly area can be tracked. The HiBall can also be mounted on a small probe or stylus, enabling extremely accurate measurements of individual objects within a large space. For example, this can be used for very rapid measurement of actual television or movie sets or other real-world objects to be combined with virtual scenes. No other device can provide comparable speed and accuracy over a wide area. 3rdTech at 1. **HiBall Beacon Array Modules** The infrared LEDs 'seen' by the HiBall Sensor are embedded in a series of ceiling mounted strips forming a 2D Beacon Array - 8 LEDs per strip; 6 strips per Beacon Array Module (BAM). These strips are designed to slip easily into a typical 'drop ceiling' with no changes required in panels, lights, vents, etc. - the more BAMs employed, the greater the range of the tracker. The arrays are highly modular — available in configurations covering as little as 64 square feet (8' x 8') or more than 1,600 square feet (40' x 40'). And no special adjustments are required to the ceiling structure — the system's precision is unaffected by typical variations in ceiling height. The HiBall Sensor and the Beacon Arrays are synchronized by a Ceiling- HiBall Interface Board (CIB), part of the system's integrated PC, which enables extremely high rates of LED 'sightings'— approximately 2,000 per second. This results in a tracker update rate of 2,000 Hz — several times faster than other commercially available wide-area trackers. Faster updates means lower latency and more accurate tracking - even with rapid movements. **AutoCalibration** The system makes use of a *single constraint at a time* (SCAAT) algorithm to compute the location and orientation of the HiBall Sensor at every LED sighting. In addition, the system incorporates *auto-calibration* — tuning the modeled location of individual LEDs on every update. This accommodates typical shifts and movements in the ceiling tiles and BAMs without loss of accuracy or performance. **Applications** The range and performance of the HiBall-3000 Tracker open up new possibilities for large-scale virtual reality such as exploring full-size architectural designs or engineering prototypes. Its precision enables largescale

CLAIM 8	HiBall
	augmented reality for applications in medicine, training and entertainment where accurate correspondence between physical reality and the virtual world are critical. **Proven Results** Developed in the Computer Science Department of the University of North Carolina at Chapel Hill (see www.cs.unc.edu/~tracker), the original HiBall tracker has been in use since 1997 and has consistently exceeded performance expectations. 3rdTech at 1.

HiBall-3000 Specifications and Performance

Hardware Components	
HiBall Optical Sensor(s)	2 7/8" tall, 2 1/8" diam, 6 OZ
Beacon Array Module (BAM)	Six 2' x 1" x 7/8" strips, 8 sq. ft.
PC-based Controller	Includes CIB I/F Board
Connections	Ethernet (VRPN), Serial (Standard Library Interface)
Software Components	
VR Peripheral Network (VRPN) support	Integrate system with other VR devices
Standard Library Interface	Compatible with existing systems
HBT Toolkit	Tools for set up, configuration and testing
HBT Library	Low-level system access
Output	Stream or point mode; XYZ coordinates; Quaternion, Euler angles or rotation matrices

3rdTech at 2.

HiBall-3000 Wide-Area Tracker Features

• Very Wide Area	Scalable to over 1,600 sq.ft.
• High Precision	Ideal for augmented reality apps and rapid scene digitizing
• High-update, low latency	Solid, high-speed tracking; no "swimming"
• Small, light sensor	Head or stylus mountable
• Easy installation	Installs in standard drop-ceilings; requires no room modifications
• Multiple sensors	Multiple participants or head plus hand tracking
• No metal/sound interference	Requires no modification of the environment
• Accurate every-where	Consistent tracking near edges of space as well as in center

3rdTech at 2.

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CLAIM 8	HiBall
	In contrast, the approach we use with the new HiBall system produces tracker reports as each new measurement is made rather than waiting to form a complete collection of observations. Because single measurements under-constrain the mathematical solution, we refer to the approach as Single-Constraint-at-a-Time or SCAAT tracking [28, 291. The key is that the single measurements provide some information about the user's state, and thus can be used to incrementally improve a previous estimate. Using a Kalman filter [15] we intentionally fuse measurements that do not individually provide sufficient information, incorporating each individual measurement immediately as it is obtained. With this approach we are able to generate estimates more frequently, with less latency, with improved accuracy, and we are able to effectively estimate the LED positions on-line concurrently while tracking the HiBall (section 5.4). We use a Kalman filter, a minimum variance stochastic estimator, to estimate the HiBall state 5, i.e. the position and orientation of the HiBall. We use a Kalman filter in part because the sensor measurement noise and the typical user motion dynamics can be modeled as normally-distributed random processes, but also because we want an efficient online method of estimation. A basic introduction to the Kalman filter can be found in Chapter 1 of [17], while a more complete introductory discussion can be found in [20], which also contains some interesting historical narrative. More extensive references can be found in [7,12,14,16,17, 301. The Kalman filter has been used previously to address similar or related problems. See for example [2, 3,9, 10, 18, 231, and most recently [113. The SCAAT approach on the other hand is an attempt to reverse this cycle. Because we intentionally use a single constraint per estimate, the algorithmic complexity is drastically reduced, which reduces the execution time, and hence the amount of motion between estimation cycles. Because the amount of motion is limited we are able to use a simple dynamic (process) model in the Kalman filter, which further simplifies the computations. In short, the simplicity of the approach means it can run very fast, which means it can produce estimates very rapidly, with low noise. The Kalman filter requires both a model of the process dynamics, and a model of the relationship between the process state and the available measurements. In part due to the simplicity of the SCAAT approach we are able to use a very simple process model. We model the continuous change in the HiBall state vector Z(t) with the simple differential equation

Exhibit E-11

CLAIM 8	HiBall
	$$\frac{d}{dt}\bar{x}(t) = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \bar{x}_1(t) \\ \bar{x}_2(t) \end{bmatrix} + \begin{bmatrix} 0 \\ \mu \end{bmatrix} u(t),$$ where the scalar $$\bar{x}_2(t) = \frac{d}{dt}\bar{x}_1(t),$$ $u(t)$ is a normally-distributed scalar white noise process, and the scalar μ represents the magnitude of the noise (the spectral density). A similar model with a distinct noise magnitude μ is used for each of the six position and orientation elements. The individual noise magnitudes are determined using an off-line simulation of the system and a non-linear optimization strategy that seeks to minimize the variance between the estimate pose and a known motion path. (See section 6.2.2.) The above differential equation represents a continuous integrated random walk, or an integrated *Wiener* or *Brownian-motion* process. Specifically, we model each component of the linear and angular HiBall velocities as random walks, and use these, assuming constant inter-measurement velocity, to estimate the six elements of the HiBall pose at time $t + \delta t$ as follows: $$\bar{x}(t + \delta t) = \begin{bmatrix} 1 & \delta t \\ 0 & 1 \end{bmatrix} \bar{x}(t). \qquad (1)$$ In addition to a relatively simple process model, the HiBall measurement model is relatively simple. For any Ceiling LED (section 4.1) and HiBall camera view (section 4.2), the 2D sensor measurement can be modeled as $$\begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} \bar{c}_x / \bar{c}_z \\ \bar{c}_y / \bar{c}_z \end{bmatrix} \qquad (2)$$

Exhibit E-11

CLAIM 8	HiBall
	where $$\begin{bmatrix} \bar{c}_x \\ \bar{c}_y \\ \bar{c}_z \end{bmatrix} = VR^T(\dot{l}_{xyz} - \bar{x}_{xyz}),$$ V is the camera viewing matrix from section 5.1, the vector $\dot{l}$ contains the position of the LED in the world, and R is a rotation matrix constructed from the orientation quaternion contained in the state vector: $$R = \text{rot\_from\_quat}(\bar{x}_q).$$ In practice we maintain the orientation of the HiBall as a combination of a global (external to the state) quaternion and a set of incremental angles as described in 128,291. Because the measurement model is non-linear we use an extended Kalman filter, making use of the Jacobian of the non-linear HiBall measurement model to transform the covariance of the Kalman filter. While this approach does not preserve the Gaussian nature of the covariance, it has been used successfully in countless applications since the introduction of the (linear) Kalman filter. Based on observations of the statistics of the HiBall filter residuals, the approach also appears to work well for the HiBall. At each estimation cycle, the next of the 26 possible views is chosen randomly. ***Four points corresponding to the comers of the LEPD sensor associated with that view are then projected into the world using the 3 by 4 viewing matrix for that view, along with the current estimates for the HiBall position and orientation.*** This projection, which is the inverse of the measurement relationship described above, results in four rays extending from the sensor into the world. The intersection of these rays and the approximate plane of the Ceiling determines a 2D bounding box on the Ceiling, within which are the candidate LEDs for the current camera view. One of the candidate LEDs is then chosen in a least-recently-used fashion to ensure a diversity of constraints. Once a particular view and LED have been chosen in this fashion, the CIB (section 4.3) is instructed to flash the LED and take a measurement as described in section 5.2. This single measurement is compared with a prediction obtained using (2), and the difference or residual is used to update the filter state and covariances using the Kalman gain matrix. The Kalman gain is computed as a combination of the current filter covariance, the measurement noise variance (section 6.2. l), and the Jacobian of the measurement model. A more detailed discussion of the HiBall Kalman filter and the SCAAT approach is beyond the scope of this paper. For additional information see [28,29]. Welch 1999 at 4-5.

Exhibit E-11

CLAIM 8	HiBall
	5.2 On-Line HiBall Measurements Upon receiving a command from the CIB (section 4.3), which is synchronized with a CIB command to the ceiling, the HiBall selects the specified LEPD and performs three measurements, one before the beacon flashes, one during the beacon flash, and one after the beacon flash. Known as "dark-light-dark", this technique is used to subtract out DC bias, low frequency noise, and background light from the beacon signal. Each LEPD has four transimpedance amplifiers, the analog outputs of which are multiplexed with those of the other LEPDs, then sampled, held, and converted by four 16-bit Delta-Sigma ADCs. Multiple samples can be integrated internally in the HiBall. The digitized LEPD data are organized into a packet for communication back to the CIB. The packets also contain information to assist in error detection. The communication protocol is simple, and while presently implemented by wire, the modulation scheme is amenable to a wireless implementation. The present wired implementation allows multiple HiBalls to be daisy chained so a single cable can support a user with multiple HiBalls. During run time we attempt to maximize the signal-to-noise ratio of the measurement with an automatic gain control scheme. For each LED we store a target signal strength constant. We compute the LED current and number of integrations (of successive A/D samples) by dividing this strength constant by the square of the distance to the LED, estimated from the current position estimate. After a reading we look at the strength of the actual measurement. If it is larger than expected we reduce the gain, if it is less than expected we increase the gain. The increase and decrease are implemented as on-line averages with scaling such that the gain constant decreases rapidly (to avoid overflow) and increases slowly. Finally we use the measured signal strength to estimate the noise on the signal using [8], and then use this as the measurement noise estimate for the Kalman filter (section 5.3). Welch 1999 at 4. As a result of these improvements the HiBall Tracker can generate over 2000 estimates per second, with less than one millisecond of latency. The system exhibits sub-millimeter translation noise and similar measured accuracy, as well as less than 0.03 degrees of orientation noise with similar measured accuracy. The weight of the user-worn HiBall is about 300 grams, making it lighter than just one camera in the 1991 system. The working volume of the current system is greater than 90 cubic meters (greater than 45 square meters of floor space, greater than 2 meters of height variation). This area can be expanded by adding more tiles, or by using checkerboard configurations which spread tiles over a larger area. Welch 1999 at 2.

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CLAIM 8	HiBall
	Both parts of the camera model are determined using a calibration procedure that relies on a goniometer (an angular positioning system) of our own design. This device consists of two servo motors mounted together such that one motor provides rotation about the vertical axis while the second motor provides rotation about an axis orthogonal to vertical. An important characteristic of the goniometer is that the rotational axes of the two motors intersect at a point at the center of the HiBall optical sphere; this point is defined as the origin of the HiBall. (It is this origin that provides the reference for the HiBall state during run time as described in section 5.3.) The rotational positioning motors were rated to provide 20 arc-second precision; we further calibrated them using a surveying grade theodolite, an angle measuring system, to 6 arc seconds. In order to determine the mapping between sensor image plane coordinates and three-space rays, we use a single LED mounted at a fixed location in the laboratory such that it is centered in the view directly out of the top lens of the HiBall. This ray defines the Z or up axis for the HiBall coordinate system. We sample other rays by rotating the goniometer motors under computer control. We sample each view with rays spaced about every 6 minutes of arc throughout the field of view. We repeat each measurement 100 times in order to reduce the effects of noise on the individual measurements and to estimate the standard deviation of the measurements. Given the tables of approximately 2500 measurements for each view, we first determine a 3 by 4 view matrix using standard linear least-squares techniques. Then we determine the deviation of each measured point from that predicted by the ideal linear model. These deviations are re-sampled into a 25 by 25 grid indexed by sensor-plane coordinates using a simple scan conversion procedure and averaging. Given a measurement from a sensor at run time we convert it to an "ideal" measurement by subtracting a deviation bi-linearly interpolated from the nearest 4 entries in the table. Welch 1999 at 3 The HiBall tracker system (Figure 2) provides six-degree-of freedom tracking of devices in real time. An outward looking infrared-sensing subsystem called a HiBall (Figure 1, lower-right) is mechanically fixed to each device to be tracked. The HiBalls view an environment containing a subsystem of fixed-location infrared beacons which we call the Ceiling. At the present time, the beacons are in fact entirely located in the ceiling of our laboratory, but could as well be located in walls or other arbitrary fixed locations. These subsystems are coordinated by a Ceiling-HiBall Interface Board (CIB) which provides communication and synchronization functions between the host computer and the attached subsystems. Each HiBall has 26 narrow (less than 6 degree) views distributed over a large solid angle. Beacons are selectively flashed in a sequence such that they are seen by many different fields of view of each HiBall. Initial acquisition is performed using a brute force search through beacon space, but once initial lock is made, the selection of beacons to flash is tailored to the fields of view of the HiBalls. Tracking is maintained using a Kalman filter-based prediction-correction algorithm known as SCAAT. This technique has been further extended to provide self-calibration of the Ceiling on-line with the tracking of the attached HiBalls.

CLAIM 8	HiBall
	Welch 1999 at 2. 4.2 The HiBall As can be seen in Figure 1 and color plate image Welch 1 the HiBall is a hollow ball having dodecahedral symmetry with lenses in the upper six faces and lateral effect photo diodes (LEPDs) on the insides of the opposing six lower faces. This immediately gives six primary fields of view, or camera systems which share the same internal air space, and whose adjacent directions of view are uniformly separated by 57 degrees. While the original intent of the shared internal air space was to save space, we subsequently realized that light entering any lens sufficiently off axis can be seen by an adjacent LEPD. As such, five secondary fields of view are provided by the top or central lens, and three secondary fields of view are provided by the five other lenses. Overall, this provides 26 fields of view which are used to sense widely separated groups of beacons in the environment. While these extra views complicate the initialization of the Kalman filter as described in section 5.5, they turn out to be of great benefit during steady-state tracking by effectively increasing the overall HiBall field of view without sacrificing resolution. Welch 1999 at 2-3. 4.3 The Ceiling-HiBall Interface Board The Ceiling-HiBalI Interface Board (CIB), shown below in Figure 4, provides communication and synchronization between a host personal computer, the Ceiling (section 4.1) and the HiBall (section 4.2). The CIB has four Ceiling ports allowing interleaving of ceiling panels for up to four simultaneous led flashes and/or higher Ceiling bandwidth for more simultaneous hiball usage. (The Ceiling bandwidth is inherently limited by LED current restrictions as described in section 4.1, but this can be increased by spatially multiplexing the Ceiling tiles.) The CIB has two tether interfaces that can communicate with up to four daisy-chained hiballs each. The full-duplex communication with the hiballs uses a modulation scheme (BPSK) allowing future wireless operation. The interface from the CIB to the host PC is the stable IEEE1284C extended parallel port (EPP) standard. The CIB comprises analog drive and receive components as well as digital logic components. The digital components implement store and forward in both directions and synchronize the timing of the LED "on" interval within the HiBall dark-light-dark intervals. The protocol supports fullduplex flow control. The data are arranged into packets containing error detection to insure data quality. Welch 1999 at 3.

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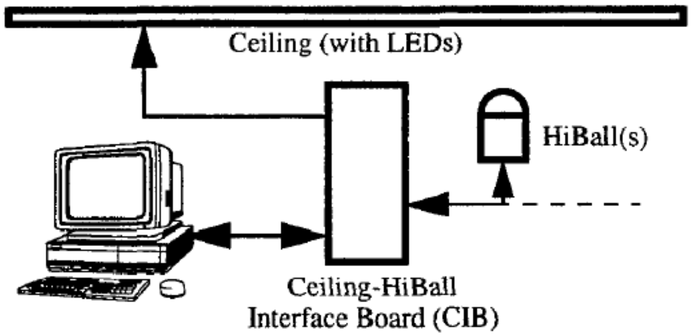
CLAIM 8	HiBall
	3. SYSTEM OVERVIEW  **Figure 2. A block diagram of the HiBall tracking system.** Welch 1999 at Fig. 2. The HiBall tracker system (Figure 2) provides six-degree-of freedom tracking of devices in real time. An outward looking infrared-sensing subsystem called a HiBall (Figure 1, lower-right) is mechanically fixed to each device to be tracked. The HiBalls view an environment containing a subsystem of fixed-location infrared beacons which we call the Ceiling. At the present time, the beacons are in fact entirely located in the ceiling of our laboratory, but could as well be located in walls or other arbitrary fixed locations. These subsystems are coordinated by a Ceiling-HiBall Interface Board (CIB) which provides communication and synchronization functions between the host computer and the attached subsystems. Each HiBall has 26 narrow (less than 6 degree) views distributed over a large solid angle. Beacons are selectively flashed in a sequence such that they are seen by many different fields of view of each HiBall. Initial acquisition is performed using a brute force search through beacon space, but once initial lock is made, the selection of beacons to flash is tailored to the fields of view of the HiBalls. Tracking is maintained using a Kalman filter-based prediction-correction algorithm known as SCAAT. This technique has been further extended to provide self-calibration of the Ceiling on-line with the tracking of the attached HiBalls. Welch 1999 at 2.

Exhibit E-11

<table>
<tr><th>CLAIM 8</th><th>HiBall</th></tr>
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4.3 The Ceiling-HiBall Interface Board

The Ceiling-HiBall Interface Board (CIB), shown below in Figure 4, provides communication and synchronization between a host personal computer, the Ceiling (section 4.1) and the HiBall (section 4.2).

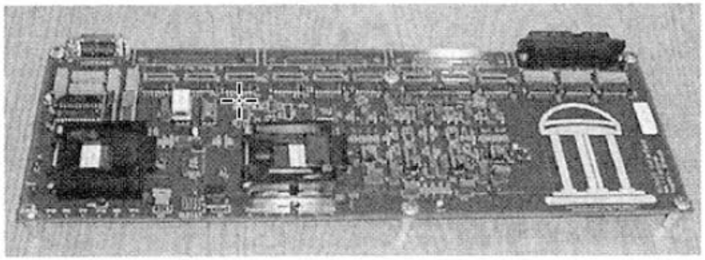

Figure 4. The Ceiling-HiBall Interface Board (CIB). The CIB shown is 19 inches, the newest revision is 14 inches.

Welch 1999 at 3.

As part of an ongoing effort to develop a system that avoids such tradeoffs, the Tracker Research Group at the University of North Carolina (http:/ /www.cs.unc.edu/-tracker) has created a wide-area optoelectronic tracking technology that lets users move freely through full-scale virtual worlds in real time. Such a capability not only enables VR applications that would otherwise be difficult or impossible to achieve-such as the exploration of life-size architectural designs and room-filling molecular models-but it is also expected to be of value to augmented reality (AR).

In AR, real and digital worlds are superimposed into one scene through the use of see-through head-mounted displays that rely either on mirrors to represent the physical world or video input. Highly accurate motion tracking is crucial because even small tracking errors can result in unacceptable misregistration between real and virtual objects. Called the HiBall Tracking System, the new technology is able to meet the needs of such applications through its implementation of four unique components: ceiling panels that house LED targets, a miniature optical- sensor cluster (the HiBall) that senses and digitizes the LED flashes, a custom interface board that facilitates communications among the various components of the system, and tracking software that processes the communications in real time.

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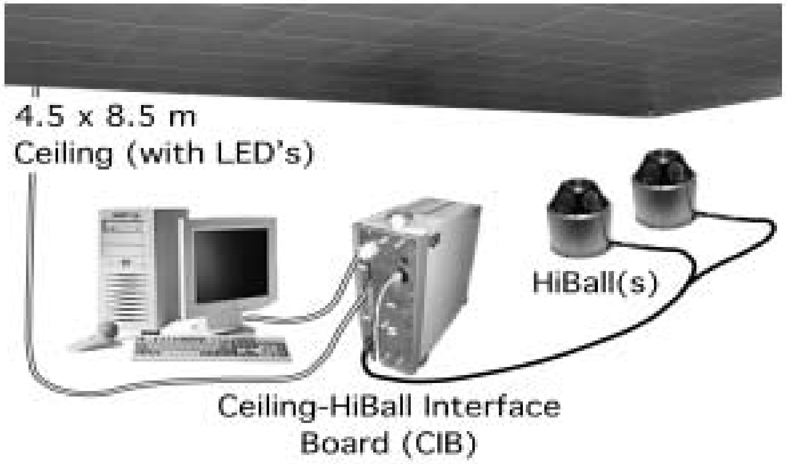
</table>

Exhibit E-11

CLAIM 8	HiBall
	On the Right Track at 2. **Inside-Out Tracking** ***Unlike traditional optical tracking methods, in which targets are attached to the object or person to be tracked and sensed by a camera in the environment, the HiBall system employs an "inside-out" approach, in which the sensors are user mounted and the LED targets are fixed in the environment. This distinction is important, says UNC research assistant professor Greg Welch, because it ensures constant sensitivity to orientation over the working area. Also, because the targets are in the ceiling tiles, the tracking environment is infinitely scalable by increasing the number of tiles.*** The HiBall itself is unique in that it does not rely on the same charged-couple devices (CCDs) that most digital cameras employ. Rather, it uses lateral-effect photo diodes (LEPDs). Unlike CCD's, LEPDs are not imaging devices. They are 2D optical sensors that produce four analog voltages, which together indicate the 2D position of the center of the light hitting the sensor. "There is no image to capture and interpret, simply four voltages to digitize, which is done right inside the HiBall;' says Welch. The control center of the tracking system is the Ceiling-HiBall Interface Board (CIB), which sends LED addresses and control signals to the ceiling to direct the flashing of the LEDs. It also communicates with the HiBall, sending control signals and receiving the digitized LEPD values. The PC tracking software sends requests to the CIB for a sample of a particular ceiling LED from a particular optical sensor. In response, the CIB tells the ceiling to flash the LED and tells the HiBall to sample the LEPD. The digitized LEPD data it receives is sent back to the PC. The system's tracking code relies on an estimation approach called SCAAT (single constraint at a time) tracking, which turns the individual LED sightings into a complete position and orientation, or pose, estimate for the HiBall. With SCAAT, individual observations are reported as soon as they're acquired, rather than at the end of a complete collection of measurements, providing some information about the user's pose. Subsequent measurements build on previous ones to improve the estimates. A filtering technique fuses a continuous sequence of these incomplete, single LED sightings into an ongoing sequence of complete estimates. To enhance the quality of the estimates and ensure low latency, thousands of LED sightings are generated per second. An autocalibration process compensates for shifts in the tiles and for inherent estimate inaccuracies. On the agenda for the HiBall system is the development of a wireless capability between the HiBall and the CIB. The researchers are also investigating more flexible LED strategies, including LED strips that can be hung from ceilings wherever needed. The group's long-term objective is to develop hybrid tracking approaches that will reduce the system's infrastructure to allow users to move beyond the lab, eventually outdoors, while maintaining system performance. In the meantime, the existing HiBall technology is headed toward commercialization by a new company called HiBall Tracker Inc., which is currently negotiating a technology license with UNC Chapel Hill.

CLAIM 8	HiBall
	On the Right Track at 2. **New Tracking Technology** The HiBall-3000 Tracker is a new approach to wide-area tracking, delivering unmatched accuracy with low latency, high update rate, and scalability to cover a very large region. Based on results of the Wide-Area Tracking research project of the Department of Computer Science of the University of North Carolina at Chapel Hill — the HiBall-3000 optical tracker achieves new levels of performance for virtual and augmented reality, simulation and training, film and video production, and entertainment. The HiBall-3000 has a unique set of features. The HiBall-3000 tracker: Scales to cover very large areas, almost without limit Maintains extraordinary precision throughout the tracking space Delivers precision unaffected by metal, magnetic fields, or noise, and built-in redundancy overcomes most line-of-sight obstructions Provides very high update rate and low latency — solid, smooth tracking even with high-speed motion. The HiBall-3000's optical tracker has been designed for the most demanding applications, achieving new levels of range, accuracy, and update rate. 3rdTech at 1. **3. SYSTEM OVERVIEW** The HiBall Tracking System consists of three main components (Figure 6). An outward-looking sensing unit we call the *HiBall* is fixed to each user to be tracked. The HiBall unit observes a subsystem of fixed-location infrared LEDs we call the *Ceiling* 1. Communication and synchronization between the host computer and these subsystems is coordinated by the *Ceiling-HiBall Interface Board* (CIB). In Section 4 we describe these components in more detail. Each HiBall observes LEDs through multiple sensor-lens *views* that are distributed over a large solid angle. LEDs are sequentially flashed (one at a time) such that they are seen via a diverse set of views for each HiBall. Initial *acquisition* is performed using a brute force search through LED space, but once initial lock is made, the selection of LEDs to flash is tailored to the views of the active HiBall units. Pose estimates are maintained using a Kalman-filter-based prediction-correction approach known as *single-constraint-at-a-time* or SCAAT tracking. This technique has been extended to provide self-calibration of the Ceiling, concurrent with HiBall tracking. In Section 5 we describe the methods we employ, including the initial acquisition process and the SCAAT approach to pose estimation, with the *autocalibration* extension. Welch HiBall at 6.

Exhibit E-11

CLAIM 8	HiBall
	 **Figure 6** Welch HiBall at Fig. 6. **4.3 The Ceiling-HiBall Interface Board** The Ceiling-HiBall Interface Board or CIB (Figure 11) provides communication and synchronization between a host personal computer, the HiBall (Section 4.1), and the Ceiling (Section 4.2). The CIB has four Ceiling ports allowing interleaving of ceiling panels for up to four simultaneous LED flashes and/or higher Ceiling bandwidth. (The Ceiling bandwidth is inherently limited by LED power restrictions as described in Section 4.2, but this can be increased by spatially multiplexing the Ceiling panels.) The CIB has two tether interfaces that can communicate with up to four daisy-chained HiBall units. The full-duplex communication with the HiBall units uses a modulation scheme (BPSK) allowing future wireless operation. The interface from the CIB to the host PC is the stable IEEE1284C extended parallel port (EPP) standard. The CIB comprises analog drive and receive components as well as digital logic components. The digital components implement store and forward in both directions and synchronize the timing of the LED "on" interval within the HiBall dark-light-dark intervals (Section 5.2). The protocol supports full-duplex flow control. The data are arranged into packets that incorporate error detection. Welch HiBall at 8-9.

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CLAIM 8	HiBall
	4. SYSTEM COMPONENTS **4.1 The HiBall** The original electro-optical tracker (Figure 3, bottom) used independently housed lateral effect photo-diode units (LEPDs) attached to a light-weight tubular framework. As it turns out, the mechanical framework would flex (distort) during use, contributing to estimation errors. In part to address this problem the HiBall sensor unit was designed as a single rigid hollow ball having dodecahedral symmetry, with lenses in the upper six faces and LEPD on the insides of the opposing six lower faces (Figure 7). This immediately gives six primary "camera" *views* uniformly spaced by 57 degrees. The views efficiently share the same internal air space, and are rigid with respect to each other. In addition, light entering any lens sufficiently off axis can be seen by a neighboring LEPD, giving rise to five secondary views through the top or central lens, and three secondary views through the five other lenses. Overall, this provides 26 fields of view which are used to sense widely separated groups of LEDs in the environment. While the extra views complicate the initialization of the Kalman filter as described in Section 5.5, they turn out to be of great benefit during steady-state tracking by effectively increasing the overall HiBall field of view without sacrificing optical sensor resolution. The lenses are simple plano-convex fixed-focus lenses. Infrared (IR) filtering is provided by fabricating the lenses themselves from RG-780 Schott glass filter material which is opaque to better than 0.001% for all visible wavelengths, and transmissive to better than 99% for IR wavelengths longer than 830 nm. The longwave filtering limit is provided by the DLS-4 LEPD silicon photodetector (UDT Sensors, Inc.) with peak responsivity at 950 nm but essentially blind above 1150 nm. The LEPDs themselves are not imaging devices; rather they detect the centroid of the luminous flux incident on the detector. The x-position of the centroid determines the ratio of two output currents, while the y-position determines the ratio of two other output currents. The total output current of each pair are commensurate, and proportional to the total incident flux. Consequently, focus is not an issue, so the simple fixed-focus lenses work well over a range of LED distances from about half a meter to infinity. The LEPDs and associated electronic components are mounted on a custom rigid-flex printed circuit board (Figure 8). This arrangement makes efficient use of the internal HiBall volume while maintaining isolation between analog and digital circuitry, and increasing reliability by alleviating the need for inter-component mechanical connectors. Figure 9 shows the physical arrangement of the folded electronics in the HiBall. Each LEPD has four transimpedance amplifiers (shown together as one "Amp" in Figure 9), the analog outputs of which are multiplexed with those of the other LEPDs, then sampled, held, and converted by four 16-bit Delta-Sigma

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	analog-to-digital (A/D) converters. Multiple samples are integrated via an accumulator. The digitized LEPD data are organized into packets for communication back to the CIB. The packets also contain information to assist in error-detection. The communication protocol is simple, and while presently implemented by wire, the modulation scheme is amenable to a wireless implementation. The present wired implementation allows multiple HiBall units to be daisy-chained so a single cable can support a user with multiple HiBall units. Welch HiBall at 6-7. **1.3 The HiBall Tracking System** In this article we describe a new and vastly improved version of the 1991 system. We call the new system the *HiBall Tracking System*. Thanks to significant improvements in hardware and software this HiBall system offers unprecedented speed, resolution, accuracy, robustness, and flexibility. The bulky and heavy sensors and backpack of the previous system have been replaced by a small *HiBall* unit (Figure 4, bottom). In addition, the precisely machined LED ceiling panels of the previous system have been replaced by looser-tolerance panels that are relatively inexpensive to make and simple to install (Figure 4, top; Figure 10). Finally, we are using an unusual Kalman-filter-based algorithm that generates very accurate pose estimates at a high rate with low latency, and simultaneously self-calibrates the system. As a result of these improvements the HiBall Tracking System can generate over 2000 pose estimates per second, with less than one millisecond of latency, better than 0.5 millimeters and 0.03 degrees of absolute error and noise, everywhere in a 4.5 by 8.5 meter room (with over two meters of height variation). The area can be expanded by adding more panels, or by using checkerboard configurations which spread panels over a larger area. The weight of the user-worn HiBall is about 300 grams, making it lighter than one optical sensor in the 1991 system. Multiple HiBall units can be daisy chained together for head or hand tracking, pose-aware input devices, or precise 3D point. Welch HiBall at 4. The HiBall tracking system resolves linear motion of less than 0.2mm and angular motions under 0.03 degrees without the distortion seen in magnetic trackers. The update rate is greater than 1500 Hz and latency is about 1ms. To our knowledge, this was the first and remains the only demonstrated scalable tracking system for HMDs. UNC HiBall Tracker at 1. **The HiBall**

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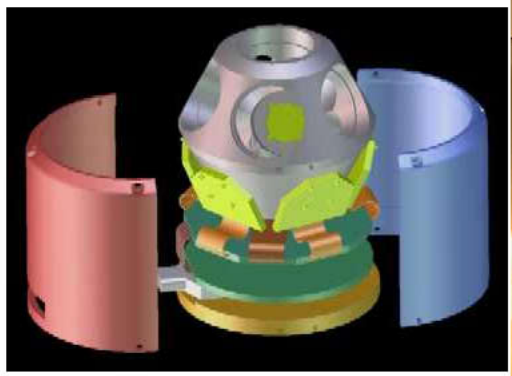
	The HiBall is a cluster of 6 lenses and 6 photodiodes arranged so that each photodiodes can view LEDs through several of the 6 lenses, providing 26 view frustra originating at the HiBall. The assembly will include signal processing and A/D conversion circuitry. The total weight is about 5 ounces, making it lighter than just one of the cameras in the previous generation ceiling tracker. The HiBall and the ceiling panel are synchronized by a custom interface board which allows very high rate of LED sightings. The hardware alone can perform more than 3,000 sightings per second, while the whole system tracks using about 1,500. UNC HiBall Tracker at 1. **The Hiball** (Shown without lenses)   UNC HiBall Tracker at 2. **The SCAAT algorithm** The UNC HiBall Tracker relies on the SCAAT (Single Constraint At A Time) algorithm to compute the user's position and orientation from the individual sightings the HiBall makes of LEDs on the ceiling panels. The algorithm makes innovative use of an Extended Kalman Filter to provide position and orientation updates after each individual LED sighting, rather than after a group of several sightings as in the previous generation of UNC ceiling tracker. In addition, SCAAT improves on previously developed auto calibration techniques to allow on-line calibration as described below. For more information see Greg Welch's SCAAT page which includes links to

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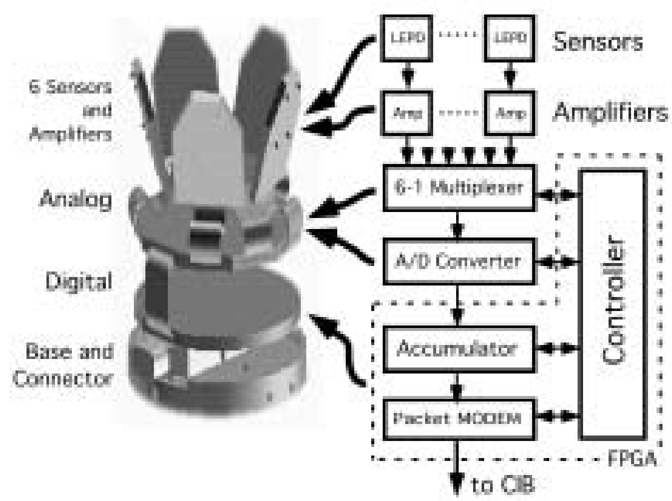
	Greg Welch and Gary Bishop's 1997 SIGGRAPH paper on SCAAT. UNC HiBall Tracker at 2. **Autocalibration** The current ceiling's lower cost design was made possible by an auto calibration process described in Gottschalk93. The SCAAT algorithm improves on this by allowing auto calibration, tuning the actual LED positions, to be performed while the system is tracking. This accommodates shifts in the tiles and LEDs which can occur during normal use. In addition this technique opens possibilities for even less initial knowledge of LED placement than the current ceiling provides. As a test and demonstration of the autocalibration abilities of SCAAT, we have intentionally raised ceiling panels from their correct position. Here Dr. Gary Bishop is shown making the adjustments. The system was given only the initial flat LED positions, but after less than ten minutes of use (successfully tracking with the misplaced panels), SCAAT had accurately adjusted its knowledge of the LED positions through displacements more than 5cm. The above visualization shows the final measured LED positions. UNC HiBall Tracker at 2-3.  **Figure 9**

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	Welch HiBall at Fig. 9. **4.2 The Ceiling** As presently implemented, the infrared LEDs are packaged in 61 centimeter square *panels*, to fit a standard false ceiling grid (Figure 10, top). Each panel uses five printed circuit boards: a main controller board and four identical transverse-mounted *strips* (bottom). Each strip is populated with eight LEDs for a total of 32 LEDs per panel. We mount the assembly on top of a metal panel such that the LEDs protrude through 32 corresponding holes. The design results in a Ceiling with a rectangular LED pattern with periods of 7.6 and 15.2 centimeters. This spacing is used for the initial estimates of the LED positions in the lab, then during normal operation the SCAAT algorithm continually refines the LED position estimates (Section 5.4). The SCAAT *autocalibration* not only relaxes design and installation constraints, but provides greater precision in the face of initial and ongoing uncertainty in the Ceiling structure. We currently have enough panels to cover an area approximately 5.5 by 8.5 meters with a total of approximately 3,000 LEDs. 1 The panels are daisy-chained to each other, and panel selection encoding is position (rather than device) dependent. Operational commands are presented to the first panel of the daisy chain. At each panel, if the panel select code is zero the controller decodes and executes the operation; else it decrements the panel select code and passes it along to the next panel (controller). Upon decoding, a particular LED is selected and the LED is energized. The LED brightness (power) is selectable for *automatic gain control* as described in Section 5.2. We currently use Siemens SFH-487P GaAs LEDs which provide both a wide angle radiation pattern and high peak power, emitting at a center wavelength of 880 nm in the near IR. These devices can be pulsed up to 2.0 Amps for a maximum duration of 200 with a 1:50 (on:off) duty cycle. While the current Ceiling architecture allows flashing of only one LED at a time, LEDs may be flashed in any sequence. As such no single LED can be flashed too long or too frequently. We include both hardware and software protection to prevent this. **4.3 The Ceiling-HiBall Interface Board** The Ceiling-HiBall Interface Board or CIB (Figure 11) provides communication and synchronization between a host personal computer, the HiBall (Section 4.1), and the Ceiling (Section 4.2). The CIB has four Ceiling ports allowing interleaving of ceiling panels for up to four simultaneous LED flashes and/or higher Ceiling bandwidth. (The Ceiling bandwidth is inherently limited by LED power restrictions as described in Section 4.2, but this can be increased by spatially multiplexing the Ceiling panels.) The CIB has two tether interfaces that can communicate with up to four daisy-chained HiBall units. The full-duplex communication with the HiBall units uses a modulation scheme (BPSK) allowing future wireless operation. The interface from the CIB to the host PC is the stable IEEE1284C extended parallel port (EPP) standard. The CIB comprises analog drive and receive

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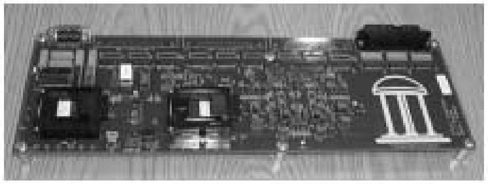
	components as well as digital logic components. The digital components implement store and forward in both directions and synchronize the timing of the LED "on" interval within the HiBall dark-light-dark intervals (Section 5.2). The protocol supports full-duplex flow control. The data are arranged into packets that incorporate error detection. Welch HiBall at 8-9.  Figure 11 Welch HiBall at Fig. 11. **The SCAAT algorithm** The UNC HiBall Tracker relies on the SCAAT (Single Constraint At A Time) algorithm to compute the user's position and orientation from the individual sightings the HiBall makes of LEDs on the ceiling panels. The algorithm makes innovative use of an Extended Kalman Filter to provide position and orientation updates after each individual LED sighting, rather than after a group of several sightings as in the previous generation of UNC ceiling tracker. In addition, SCAAT improves on previously developed auto calibration techniques to allow on-line calibration as described below. For more information see Greg Welch's SCAAT page which includes links to Greg Welch and Gary Bishop's 1997 SIGGRAPH paper on SCAAT. UNC HiBall Tracker at 2. **Autocalibration** The current ceiling's lower cost design was made possible by an auto calibration process described in Gottschalk93. The SCAAT algorithm improves on this by allowing auto calibration, tuning the actual LED positions, to be performed while the system is tracking. This accommodates shifts in the tiles and LEDs which can occur during normal use. In addition this technique opens possibilities for even less initial knowledge of LED placement than the current ceiling provides.

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	As a test and demonstration of the autocalibration abilities of SCAAT, we have intentionally raised ceiling panels from their correct position. Here Dr. Gary Bishop is shown making the adjustments. The system was given only the initial flat LED positions, but after less than ten minutes of use (successfully tracking with the misplaced panels), SCAAT had accurately adjusted its knowledge of the LED positions through displacements more than 5cm. The above visualization shows the final measured LED positions. UNC HiBall Tracker at 2-3. **6.2.2 Complete System Simulations.** To produce realistic data for developing and tuning our algorithms we collected several motion paths *(*sequences of pose estimates) from our first generation electro-optical tracker (Figure 3) at its 70 Hz maximum report rate. These paths were recorded from both naive users visiting our monthly "demo days" and from experienced users in our labs. In the same fashion as we had done for (Azuma & Bishop, 1994a) we filtered the raw path data with a non-causal zero-phase-shift low-pass filter to eliminate energy above 2 Hz. The output of the low-pass filtering was then re-sampled at whatever rate we wanted to run the simulated tracker, usually 1000 Hz. For the purposes of our simulations we considered these resampled paths to be the "truth"—a perfect representation of a user's motion. Tracking error was determined by comparing the "true" path to the estimated path produced by the tracker. The simulator reads camera models describing the 26 views, the sensor noise parameters, the LED positions and their expected error, and the motion path described above. Before beginning the simulation, the LED positions are perturbed from their ideal positions by adding normally distributed error to each axis. Then, for each simulated cycle of operation, the "true" pose are updated using the input motion path. Next, a view is chosen and a visible LED within that view is selected, and the image-plane coordinates of the LED on the chosen sensor are computed using the camera model for the view and the LED as described in Section 5.3. These sensor coordinates are then perturbed based on the sensor noise model (Section 6.2.1) using the distance and angle to the LED. Now these noise corrupted sensor readings are fed to the SCAAT filter to produce an updated position estimate. The position estimate is compared to the true position to produce a scalar error metric described next. Welch HiBall at 16-17. **5.4 On-line LED Autocalibration** Along with the benefit of simplicity and speed, the SCAAT approach offers the additional capability of being able to estimate the 3D positions of the LEDs in the world concurrently with the pose of the HiBall, on line, in real time. This capability is a tremendous benefit in terms of the accuracy and noise characteristics of the estimates. Accurate LED position estimates are so important that prior to the introduction of the SCAAT approach a specialized off-line approach was developed to address the problem (Gottschalk & Hughes, 1993).

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	The method we now use for autocalibration involves defining a distinct SCAAT Kalman filter for each LED. Specifically, for each LED we maintain a state $\bar{l}$ (estimate of the 3D position) and a 3x3 Kalman filter covariance. At the beginning of each estimation cycle we form an augmented state vector $\hat{x}$ using the appropriate LED state and the current HiBall state: $\hat{x} = [\bar{x}^{\mathrm{T}}, \bar{l}^{\mathrm{T}}]^{\mathrm{T}}$. Similarly we augment the Kalman filter error covariance matrix with that of the LED filter. We then follow the normal steps outlined in Section 5.3, with the result being that the LED portion of the filter state and covariance is updated in accordance with the measurement residual. At the end of the cycle we extract the LED portions of the state and covariance from the augmented filter, and save them externally. The effect is that as the system is being used, it continually refines its estimates of the LED positions, thereby continually improving its estimates of the HiBall pose. Again, for additional information see (Welch, 1996; Welch & Bishop, 1997). Welch HiBall at 13. The Kalman filter requires both a model of the process dynamics, and a model of the relationship between the process state and the available measurements. In part due to the simplicity of the SCAAT approach we are able to use a simple PV (position-velocity) process model (Brown & Hwang, 1992). Consider the simple example state vector $\bar{x}(t) = [x_p(t), x_v(t)]^{\mathrm{T}}$ where the first element $x_p(t)$ is the pose (position or orientation) and the second element $x_v(t)$ is the corresponding velocity, i.e. $x_v(t) = \frac{d}{dt}x_p(t)$. We model the continuous change in the HiBall state with the simple differential equation $$\frac{d}{dt}\bar{x}(t) = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} x_p(t) \\ x_v(t) \end{bmatrix} + \begin{bmatrix} 0 \\ \mu \end{bmatrix} u(t), \qquad (1)$$ where *u(t)* is a normally-distributed white (in the frequency spectrum) scalar noise process, and the scalar μ represents the magnitude or *spectral density* of the noise. We use a similar model with a distinct noise process for each of the six pose elements. We determine the individual noise magnitudes using an off-line simulation of the system and a non-linear optimization strategy that seeks to minimize the variance between the estimated pose and a known motion path. (See Section 6.2.2.) The differential equation (1) represents a continuous integrated random walk, or an integrated *Wiener* or *Brownian-motion* process. Specifically, we model each component of the linear and angular HiBall velocities as a random walk, and then use these (assuming constant inter-measurement velocity) to estimate the HiBall pose at time $t + \delta t$ as follows:

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	$$\bar{x}(t+\delta t) = \begin{bmatrix} 1 & \delta t \\ 0 & 1 \end{bmatrix} \bar{x}(t) \qquad (2)$$ for each of the six pose elements. In addition to a relatively simple process model, the HiBall measurement model is relatively simple. For any Ceiling LED (Section 4.2) and HiBall view (Section 4.1), the 2D sensor measurement can be modeled as $$\begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} c_x / c_z \\ c_y / c_z \end{bmatrix} \qquad (3)$$ where $$\begin{bmatrix} c_x \\ c_y \\ c_z \end{bmatrix} = VR^{T}(\hat{l}_{xyz} - \bar{x}_{xyz}), \qquad (4)$$ is the camera viewing matrix from Section 5.1, is the position of the LED in the world, is the position of the HiBall in the world, and is a rotation matrix corresponding to the orientation of the HiBall in the world. In practice we maintain the orientation of the HiBall as a combination of a global (external to the state) quaternion and a set of incremental angles as described in (Welch, 1996; Welch & Bishop, 1997). Welch HiBall at 11-12. **5.2 On-Line HiBall Measurements** Upon receiving a command from the CIB (Section 4.3), which is synchronized with a CIB command to the ceiling, the HiBall selects the specified LEPD and performs three measurements, one before the LED flashes, one during the LED flash, and one after the LED flash. Known as “dark-light-dark”, this technique is used to subtract out DC bias, low frequency noise, and background light from the LED signal. We then convert the measured sensor coordinates to “ideal” coordinates using the calibration tables described in Section 5.1. In addition, during run time we attempt to maximize the signal-to-noise ratio of the measurement with an automatic gain control scheme. For each LED we store a target signal strength factor. We compute the LED current and number of integrations (of successive accumulated A/D samples) by dividing this strength factor by the square of the distance to the LED, estimated from the current position estimate. After a reading we look at the strength of the actual measurement. If it is larger than expected we reduce the gain, if it is less than expected we increase the gain. The increase and decrease are implemented as on-line averages with scaling such that the gain

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	factor decreases rapidly (to avoid overflow) and increases slowly. Finally we use the measured signal strength to estimate the noise on the signal using (Chi, 1995), and then use this as the measurement noise estimate for the Kalman filter (Section 5.3). Welch HiBall at 9-10. *See also* /hiball/src/libs/tracker and /cib, including but not limited to the following: /hiball/src/libs/tracker/acquire.cpp /hiball/src/libs/tracker/acquire.h /hiball/src/libs/tracker/hiballfilter.h /hiball/src/libs/tracker/hiballfilter.cpp *See also* Defendants' Invalidity Contentions for further discussion.

G. DEPENDENT CLAIM 9

CLAIM 9	HiBall
[9] The method of claim 8 wherein the target comprises a natural feature in an environment.	At least under Plaintiffs' apparent infringement theory, HiBall discloses, either expressly or inherently, the method of claim 8 wherein the target comprises a natural feature in an environment. In the alternative, this element would be obvious over HiBall in light of the other references disclosed in Defendants' Invalidity Contentions and/or the knowledge of one of ordinary skill in the art. *See, e.g.*: 4.2 The HiBall As can be seen in Figure 1 and color plate image Welch 1 the HiBall is a hollow ball having dodecahedral symmetry with lenses in the upper six faces and lateral effect photo diodes (LEPDs) on the insides of the opposing six lower

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	faces. This immediately gives six primary fields of view, or camera systems which share the same internal air space, and whose adjacent directions of view are uniformly separated by 57 degrees. While the original intent of the shared internal air space was to save space, we subsequently realized that light entering any lens sufficiently off axis can be seen by an adjacent LEPD. As such, five secondary fields of view are provided by the top or central lens, and three secondary fields of view are provided by the five other lenses. ***Overall, this provides 26 fields of view which are used to sense widely separated groups of beacons in the environment.*** While these extra views complicate the initialization of the Kalman filter as described in section 5.5, they turn out to be of great benefit during steady-state tracking by effectively increasing the overall HiBall field of view without sacrificing resolution. Welch 1999 at 2-3. 4.3 The Ceiling-HiBall Interface Board The Ceiling-HiBalI Interface Board (CIB), shown below in Figure 4, provides communication and synchronization between a host personal computer, the Ceiling (section 4.1) and the HiBall (section 4.2). The CIB has four Ceiling ports allowing interleaving of ceiling panels for up to four simultaneous led flashes and/or higher Ceiling bandwidth for more simultaneous hiball usage. (The Ceiling bandwidth is inherently limited by LED current restrictions as described in section 4.1, but this can be increased by spatially multiplexing the Ceiling tiles.) The CIB has two tether interfaces that can communicate with up to four daisy-chained hiballs each. The full-duplex communication with the hiballs uses a modulation scheme (BPSK) allowing future wireless operation. The interface from the CIB to the host PC is the stable IEEE1284C extended parallel port (EPP) standard. The CIB comprises analog drive and receive components as well as digital logic components. The digital components implement store and forward in both directions and synchronize the timing of the LED "on" interval within the HiBall dark-light-dark intervals. The protocol supports fullduplex flow control. The data are arranged into packets containing error detection to insure data quality. Welch 1999 at 3. In contrast, the approach we use with the new HiBall system produces tracker reports as each new measurement is made rather than waiting to form a complete collection of observations. Because single measurements under-constrain the mathematical solution, we refer to the approach as Single-Constraint-at-a-Time or SCAAT tracking [28, 291. The key is that the single measurements provide some information about the user's state, and thus can be used to incrementally improve a previous estimate. Using a Kalman filter [15] we intentionally fuse measurements that do not individually provide sufficient information, incorporating each individual measurement immediately as it is obtained. With this approach we are able to generate estimates more frequently, with less latency, with

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	improved accuracy, and we are able to effectively estimate the LED positions on-line concurrently while tracking the HiBall (section 5.4). We use a Kalman filter, a minimum variance stochastic estimator, to estimate the HiBall state 5, i.e. the position and orientation of the HiBall. We use a Kalman filter in part because the sensor measurement noise and the typical user motion dynamics can be modeled as normally-distributed random processes, but also because we want an efficient online method of estimation. A basic introduction to the Kalman filter can be found in Chapter 1 of [17], while a more complete introductory discussion can be found in [20], which also contains some interesting historical narrative. More extensive references can be found in [7,12,14,16,17, 301. The Kalman filter has been used previously to address similar or related problems. See for example [2, 3,9, 10, 18, 231, and most recently [113. The SCAAT approach on the other hand is an attempt to reverse this cycle. Because we intentionally use a single constraint per estimate, the algorithmic complexity is drastically reduced, which reduces the execution time, and hence the amount of motion between estimation cycles. Because the amount of motion is limited we are able to use a simple dynamic (process) model in the Kalman filter, which further simplifies the computations. In short, the simplicity of the approach means it can run very fast, which means it can produce estimates very rapidly, with low noise. The Kalman filter requires both a model of the process dynamics, and a model of the relationship between the process state and the available measurements. In part due to the simplicity of the SCAAT approach we are able to use a very simple process model. We model the continuous change in the HiBall state vector Z(t) with the simple differential equation $$\frac{d}{dt}\bar{x}(t) = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \bar{x}_1(t) \\ \bar{x}_2(t) \end{bmatrix} + \begin{bmatrix} 0 \\ \mu \end{bmatrix} u(t),$$ where the scalar $$\bar{x}_2(t) = \frac{d}{dt}\bar{x}_1(t),$$

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	$u(t)$ is a normally-distributed scalar white noise process, and the scalar μ represents the magnitude of the noise (the spectral density). A similar model with a distinct noise magnitude μ is used for each of the six position and orientation elements. The individual noise magnitudes are determined using an off-line simulation of the system and a non-linear optimization strategy that seeks to minimize the variance between the estimate pose and a known motion path. (See section 6.2.2.) The above differential equation represents a continuous integrated random walk, or an integrated *Wiener* or *Brownian-motion* process. Specifically, we model each component of the linear and angular HiBall velocities as random walks, and use these, assuming constant inter-measurement velocity, to estimate the six elements of the HiBall pose at time $t + \delta t$ as follows: $$\bar{x}(t+\delta t) = \begin{bmatrix} 1 & \delta t \\ 0 & 1 \end{bmatrix} \bar{x}(t). \quad (1)$$ In addition to a relatively simple process model, the HiBall measurement model is relatively simple. For any Ceiling LED (section 4.1) and HiBall camera view (section 4.2), the 2D sensor measurement can be modeled as $$\begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} \bar{c}_x / \bar{c}_z \\ \bar{c}_y / \bar{c}_z \end{bmatrix} \quad (2)$$ where $$\begin{bmatrix} \bar{c}_x \\ \bar{c}_y \\ \bar{c}_z \end{bmatrix} = VR^T(\bar{l}_{xyz} - \bar{x}_{xyz}),$$ V is the camera viewing matrix from section 5.1, the vector $\bar{l}$ contains the position of the LED in the world, and R is a rotation matrix constructed from the orientation quaternion contained in the state vector: $$R = \text{rot\_from\_quat}(\bar{x}_q).$$

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CLAIM 9	HiBall
	In practice we maintain the orientation of the HiBall as a combination of a global (external to the state) quaternion and a set of incremental angles as described in 128,291. Because the measurement model is non-linear we use an extended Kalman filter, making use of the Jacobian of the non-linear HiBall measurement model to transform the covariance of the Kalman filter. While this approach does not preserve the Gaussian nature of the covariance, it has been used successfully in countless applications since the introduction of the (linear) Kalman filter. Based on observations of the statistics of the HiBall filter residuals, the approach also appears to work well for the HiBall. At each estimation cycle, the next of the 26 possible views is chosen randomly. Four points corresponding to the comers of the LEPD sensor associated with that view are then projected into the world using the 3 by 4 viewing matrix for that view, along with the current estimates for the HiBall position and orientation. This projection, which is the inverse of the measurement relationship described above, results in four rays extending from the sensor into the world. The intersection of these rays and the approximate plane of the Ceiling determines a 2D bounding box on the Ceiling, within which are the candidate LEDs for the current camera view. One of the candidate LEDs is then chosen in a least-recently-used fashion to ensure a diversity of constraints. Once a particular view and LED have been chosen in this fashion, the CIB (section 4.3) is instructed to flash the LED and take a measurement as described in section 5.2. This single measurement is compared with a prediction obtained using (2), and the difference or residual is used to update the filter state and covariances using the Kalman gain matrix. The Kalman gain is computed as a combination of the current filter covariance, the measurement noise variance (section 6.2. l), and the Jacobian of the measurement model. A more detailed discussion of the HiBall Kalman filter and the SCAAT approach is beyond the scope of this paper. For additional information see [28,29]. Welch 1999 at 4-5. 5.2 On-Line HiBall Measurements Upon receiving a command from the CIB (section 4.3), which is synchronized with a CIB command to the ceiling, the HiBall selects the specified LEPD and performs three measurements, one before the beacon flashes, one during the beacon flash, and one after the beacon flash. Known as "dark-light-dark", this technique is used to subtract out DC bias, low frequency noise, and background light from the beacon signal. Each LEPD has four transimpedance amplifiers, the analog outputs of which are multiplexed with those of the other LEPDs, then sampled, held, and converted by four 16-bit Delta-Sigma ADCs. Multiple samples can be integrated internally in the HiBall. The digitized LEPD data are organized into a packet for communication back to the CIB. The packets also contain information to assist in error detection. The communication protocol is simple, and while presently implemented by wire, the modulation scheme is amenable to a wireless implementation. The present wired implementation allows multiple HiBalls to be daisy chained so a single cable can support a user with multiple HiBalls. During run

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CLAIM 9	HiBall
	time we attempt to maximize the signal-to-noise ratio of the measurement with an automatic gain control scheme. For each LED we store a target signal strength constant. We compute the LED current and number of integrations (of successive A/D samples) by dividing this strength constant by the square of the distance to the LED, estimated from the current position estimate. After a reading we look at the strength of the actual measurement. If it is larger than expected we reduce the gain, if it is less than expected we increase the gain. The increase and decrease are implemented as on-line averages with scaling such that the gain constant decreases rapidly (to avoid overflow) and increases slowly. Finally we use the measured signal strength to estimate the noise on the signal using [8], and then use this as the measurement noise estimate for the Kalman filter (section 5.3). Welch 1999 at 4. As a result of these improvements the HiBall Tracker can generate over 2000 estimates per second, with less than one millisecond of latency. The system exhibits sub-millimeter translation noise and similar measured accuracy, as well as less than 0.03 degrees of orientation noise with similar measured accuracy. The weight of the user-worn HiBall is about 300 grams, making it lighter than just one camera in the 1991 system. The working volume of the current system is greater than 90 cubic meters (greater than 45 square meters of floor space, greater than 2 meters of height variation). This area can be expanded by adding more tiles, or by using checkerboard configurations which spread tiles over a larger area. Welch 1999 at 2. Both parts of the camera model are determined using a calibration procedure that relies on a goniometer (an angular positioning system) of our own design. This device consists of two servo motors mounted together such that one motor provides rotation about the vertical axis while the second motor provides rotation about an axis orthogonal to vertical. An important characteristic of the goniometer is that the rotational axes of the two motors intersect at a point at the center of the HiBall optical sphere; this point is defined as the origin of the HiBall. (It is this origin that provides the reference for the HiBall state during run time as described in section 5.3.) The rotational positioning motors were rated to provide 20 arc-second precision; we further calibrated them using a surveying grade theodolite, an angle measuring system, to 6 arc seconds. In order to determine the mapping between sensor image plane coordinates and three-space rays, we use a single LED mounted at a fixed location in the laboratory such that it is centered in the view directly out of the top lens of the HiBall. This ray defines the Z or up axis for the HiBall coordinate system. We sample other rays by rotating the goniometer motors under computer control. We sample each view with rays spaced about every 6 minutes of arc throughout the field of view. We repeat each measurement

CLAIM 9	HiBall
	100 times in order to reduce the effects of noise on the individual measurements and to estimate the standard deviation of the measurements. Given the tables of approximately 2500 measurements for each view, we first determine a 3 by 4 view matrix using standard linear least-squares techniques. Then we determine the deviation of each measured point from that predicted by the ideal linear model. These deviations are re-sampled into a 25 by 25 grid indexed by sensor-plane coordinates using a simple scan conversion procedure and averaging. Given a measurement from a sensor at run time we convert it to an "ideal" measurement by subtracting a deviation bi-linearly interpolated from the nearest 4 entries in the table. Welch 1999 at 3 The HiBall tracker system (Figure 2) provides six-degree-of freedom tracking of devices in real time. An outward looking infrared-sensing subsystem called a HiBall (Figure 1, lower-right) is mechanically fixed to each device to be tracked***. The HiBalls view an environment containing a subsystem of fixed-location infrared beacons which we call the Ceiling.*** At the present time, the beacons are in fact entirely located in the ceiling of our laboratory, but could as well be located in walls or other arbitrary fixed locations. These subsystems are coordinated by a Ceiling-HiBall Interface Board (CIB) which provides communication and synchronization functions between the host computer and the attached subsystems. Each HiBall has 26 narrow (less than 6 degree) views distributed over a large solid angle. Beacons are selectively flashed in a sequence such that they are seen by many different fields of view of each HiBall. Initial acquisition is performed using a brute force search through beacon space, but once initial lock is made, the selection of beacons to flash is tailored to the fields of view of the HiBalls. Tracking is maintained using a Kalman filter-based prediction-correction algorithm known as SCAAT. This technique has been further extended to provide self-calibration of the Ceiling on-line with the tracking of the attached HiBalls. Welch 1999 at 2.

Exhibit E-11

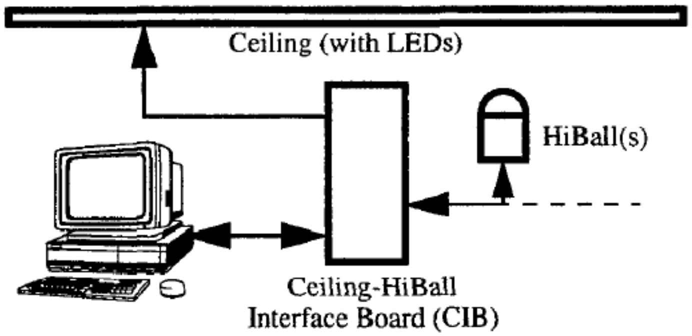
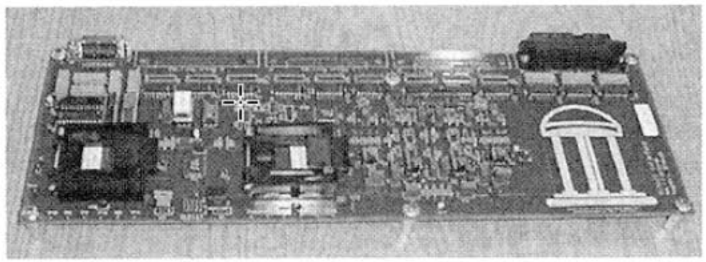
CLAIM 9	HiBall
	3. SYSTEM OVERVIEW  **Figure 2. A block diagram of the HiBall tracking system.** Welch 1999 at Fig. 2. The HiBall tracker system (Figure 2) provides six-degree-of freedom tracking of devices in real time. An outward looking infrared-sensing subsystem called a HiBall (Figure 1, lower-right) is mechanically fixed to each device to be tracked. The HiBalls view an environment containing a subsystem of fixed-location infrared beacons which we call the Ceiling. At the present time, the beacons are in fact entirely located in the ceiling of our laboratory, but could as well be located in walls or other arbitrary fixed locations. These subsystems are coordinated by a Ceiling-HiBall Interface Board (CIB) which provides communication and synchronization functions between the host computer and the attached subsystems. Each HiBall has 26 narrow (less than 6 degree) views distributed over a large solid angle. Beacons are selectively flashed in a sequence such that they are seen by many different fields of view of each HiBall. Initial acquisition is performed using a brute force search through beacon space, but once initial lock is made, the selection of beacons to flash is tailored to the fields of view of the HiBalls. Tracking is maintained using a Kalman filter-based prediction-correction algorithm known as SCAAT. This technique has been further extended to provide self-calibration of the Ceiling on-line with the tracking of the attached HiBalls. Welch 1999 at 2.

Exhibit E-11

CLAIM 9	HiBall
	4.3 The Ceiling-HiBall Interface Board The Ceiling-HiBall Interface Board (CIB), shown below in Figure 4, provides communication and synchronization between a host personal computer, the Ceiling (section 4.1) and the HiBall (section 4.2).  **Figure 4. The Ceiling-HiBall Interface Board (CIB). The CIB shown is 19 inches, the newest revision is 14 inches.** Welch 1999 at 3. As part of an ongoing effort to develop a system that avoids such tradeoffs, the Tracker Research Group at the University of North Carolina (http:/ /www.cs.unc.edu/-tracker) has created a wide-area optoelectronic tracking technology that lets users move freely through full-scale virtual worlds in real time. Such a capability not only enables VR applications that would otherwise be difficult or impossible to achieve-such as the exploration of life-size architectural designs and room-filling molecular models-but it is also expected to be of value to augmented reality (AR). In AR, real and digital worlds are superimposed into one scene through the use of see-through head-mounted displays that rely either on mirrors to represent the physical world or video input. Highly accurate motion tracking is crucial because even small tracking errors can result in unacceptable misregistration between real and virtual objects. Called the HiBall Tracking System, the new technology is able to meet the needs of such applications through its implementation of four unique components: ceiling panels that house LED targets, a miniature optical- sensor cluster (the HiBall) that senses and digitizes the LED flashes, a custom interface board that facilitates communications among the various components of the system, and tracking software that processes the communications in real time. On the Right Track at 2.

CLAIM 9	HiBall
	Inside-Out Tracking Unlike traditional optical tracking methods, in which targets are attached to the object or person to be tracked and sensed by a camera in the environment, the HiBall system employs an "inside-out" approach, in which the sensors are user mounted and t***he LED targets are fixed in the environment.*** This distinction is important, says UNC research assistant professor Greg Welch, because it ensures constant sensitivity to orientation over the working area. Also, because the targets are in the ceiling tiles, ***the tracking environment*** is infinitely scalable by increasing the number of tiles. The HiBall itself is unique in that it does not rely on the same charged-couple devices (CCDs) that most digital cameras employ. Rather, it uses lateral-effect photo diodes (LEPDs). Unlike CCD's, LEPDs are not imaging devices. They are 2D optical sensors that produce four analog voltages, which together indicate the 2D position of the center of the light hitting the sensor. "There is no image to capture and interpret, simply four voltages to digitize, which is done right inside the HiBall;' says Welch. The control center of the tracking system is the Ceiling-HiBall Interface Board (CIB), which sends LED addresses and control signals to the ceiling to direct the flashing of the LEDs. It also communicates with the HiBall, sending control signals and receiving the digitized LEPD values. The PC tracking software sends requests to the CIB for a sample of a particular ceiling LED from a particular optical sensor. In response, the CIB tells the ceiling to flash the LED and tells the HiBall to sample the LEPD. The digitized LEPD data it receives is sent back to the PC. The system's tracking code relies on an estimation approach called SCAAT (single constraint at a time) tracking, which turns the individual LED sightings into a complete position and orientation, or pose, estimate for the HiBall. With SCAAT, individual observations are reported as soon as they're acquired, rather than at the end of a complete collection of measurements, providing some information about the user's pose. Subsequent measurements build on previous ones to improve the estimates. A filtering technique fuses a continuous sequence of these incomplete, single LED sightings into an ongoing sequence of complete estimates. To enhance the quality of the estimates and ensure low latency, thousands of LED sightings are generated per second. An autocalibration process compensates for shifts in the tiles and for inherent estimate inaccuracies. On the agenda for the HiBall system is the development of a wireless capability between the HiBall and the CIB. The researchers are also investigating more flexible LED strategies, including LED strips that can be hung from ceilings wherever needed. The group's long-term objective is to develop hybrid tracking approaches that will reduce the system's infrastructure to allow users to move beyond the lab, eventually outdoors, while maintaining system performance. In the meantime, the existing HiBall technology is headed toward commercialization by a new company called HiBall Tracker Inc., which is currently negotiating a technology license with UNC Chapel Hill. On the Right Track at 2.

CLAIM 9	HiBall
	New Tracking Technology The HiBall-3000 Tracker is a new approach to wide-area tracking, delivering unmatched accuracy with low latency, high update rate, and scalability to cover a very large region. Based on results of the Wide-Area Tracking research project of the Department of Computer Science of the University of North Carolina at Chapel Hill — the HiBall-3000 optical tracker achieves new levels of performance for virtual and augmented reality, simulation and training, film and video production, and entertainment. The HiBall-3000 has a unique set of features. The HiBall-3000 tracker: Scales to cover very large areas, almost without limit Maintains extraordinary precision throughout the tracking space Delivers precision unaffected by metal, magnetic fields, or noise, and built-in redundancy overcomes most line-of-sight obstructions Provides very high update rate and low latency — solid, smooth tracking even with high-speed motion. The HiBall-3000's optical tracker has been designed for the most demanding applications, achieving new levels of range, accuracy, and update rate. 3rdTech at 1. **The HiBall-3000 Optical Sensor** The HiBall-3000 tracker system is composed of two key integrated components; the HiBall Optical Sensor and the HiBall Ceiling Beacon Arrays. The HiBall Optical Sensor is composed of 6 lenses and photodiodes arranged so that each photodiode can 'view' infrared LEDs, in the Beacon Arrays mounted on the ceiling, through several of the 6 lenses. The assembly includes signal processing and analog-to-digital conversion circuitry. The total weight is about 6 ounces, making it light enough to comfortably mount on a headmounted display or hand-held device. By locating the sensors on the person or object being tracked — *inside-out tracking* — sensitivity around the working area is increased and the tracker area scales almost without limit. An entire lab, movie set, or assembly area can be tracked. The HiBall can also be mounted on a small probe or stylus, enabling extremely accurate measurements of individual objects within a large space. For example, this can be used for very rapid measurement of actual television or movie sets or other real-world objects to be combined with virtual scenes. No other device can provide comparable speed and accuracy over a wide area. 3rdTech at 1. **HiBall Beacon Array Modules** The infrared LEDs 'seen' by the HiBall Sensor are embedded in a series of ceiling mounted strips forming a 2D Beacon Array - 8 LEDs per strip; 6 strips per Beacon Array Module (BAM). These strips are designed to slip easily

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CLAIM 9	HiBall
	into a typical 'drop ceiling' with no changes required in panels, lights, vents, etc. - the more BAMs employed, the greater the range of the tracker. The arrays are highly modular — available in configurations covering as little as 64 square feet (8' x 8') or more than 1,600 square feet (40' x 40'). And no special adjustments are required to the ceiling structure — the system's precision is unaffected by typical variations in ceiling height. The HiBall Sensor and the Beacon Arrays are synchronized by a Ceiling- HiBall Interface Board (CIB), part of the system's integrated PC, which enables extremely high rates of LED 'sightings'— approximately 2,000 per second. This results in a tracker update rate of 2,000 Hz — several times faster than other commercially available wide-area trackers. Faster updates means lower latency and more accurate tracking - even with rapid movements. **AutoCalibration** The system makes use of a *single constraint at a time* (SCAAT) algorithm to compute the location and orientation of the HiBall Sensor at every LED sighting. In addition, the system incorporates *auto-calibration* — tuning the modeled location of individual LEDs on every update. This accommodates typical shifts and movements in the ceiling tiles and BAMs without loss of accuracy or performance. **Applications** The range and performance of the HiBall-3000 Tracker open up new possibilities for large-scale virtual reality such as exploring full-size architectural designs or engineering prototypes. Its precision enables largescale augmented reality for applications in medicine, training and entertainment where accurate correspondence between physical reality and the virtual world are critical. **Proven Results** Developed in the Computer Science Department of the University of North Carolina at Chapel Hill (see www.cs.unc.edu/~tracker), the original HiBall tracker has been in use since 1997 and has consistently exceeded performance expectations. 3rdTech at 1.

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CLAIM 9	HiBall

HiBall-3000 Specifications and Performance

Hardware Components	
HiBall Optical Sensor(s)	2 7/8" tall, 2 1/8" diam, 6 OZ
Beacon Array Module (BAM)	Six 2' x 1" x 7/8" strips, 8 sq. ft.
PC-based Controller	Includes CIB I/F Board
Connections	Ethernet (VRPN), Serial (Standard Library Interface)
Software Components	
VR Peripheral Network (VRPN) support	Integrate system with other VR devices
Standard Library Interface	Compatible with existing systems
HBT Toolkit	Tools for set up, configuration and testing
HBT Library	Low-level system access
Output	Stream or point mode; XYZ coordinates; Quaternion, Euler angles or rotation matrices

3rdTech at 2.

HiBall-3000 Wide-Area Tracker Features

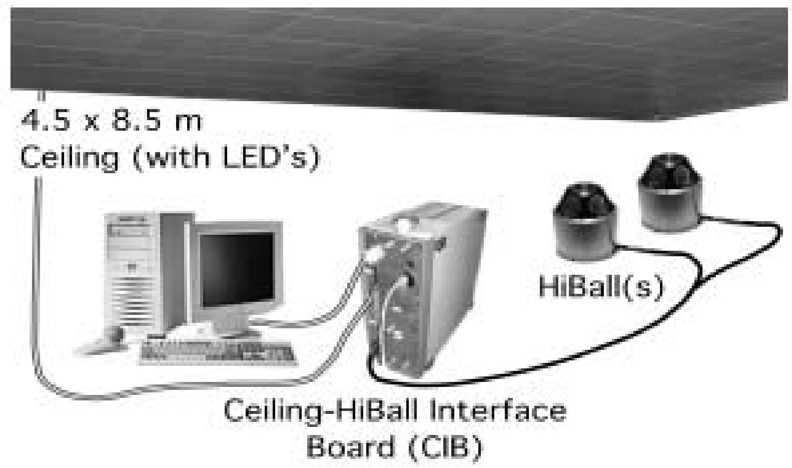
• Very Wide Area	Scalable to over 1,600 sq.ft.
• High Precision	Ideal for augmented reality apps and rapid scene digitizing
• High-update, low latency	Solid, high-speed tracking; no "swimming"
• Small, light sensor	Head or stylus mountable
• Easy installation	Installs in standard drop ceilings; requires no room modifications
• Multiple sensors	Multiple participants or head plus hand tracking
• No metal/sound interference	Requires no modification of the environment
• Accurate every-where	Consistent tracking near edges of space as well as in center

3rdTech at 2.

3. SYSTEM OVERVIEW

The HiBall Tracking System consists of three main components (Figure 6). An outward-looking sensing unit we call the *HiBall* is fixed to each user to be tracked. The HiBall unit observes a subsystem of fixed-location infrared LEDs we call the *Ceiling* 1. Communication and synchronization between the host computer and these subsystems is coordinated by the *Ceiling-HiBall Interface Board* (CIB). In Section 4 we describe these components in more detail. Each HiBall observes LEDs through multiple sensor-lens *views* that are distributed

Exhibit E-11

CLAIM 9	HiBall
	over a large solid angle. LEDs are sequentially flashed (one at a time) such that they are seen via a diverse set of views for each HiBall. Initial *acquisition* is performed using a brute force search through LED space, but once initial lock is made, the selection of LEDs to flash is tailored to the views of the active HiBall units. Pose estimates are maintained using a Kalman-filter-based prediction-correction approach known as *single-constraint-at-a-time* or SCAAT tracking. This technique has been extended to provide self-calibration of the Ceiling, concurrent with HiBall tracking. In Section 5 we describe the methods we employ, including the initial acquisition process and the SCAAT approach to pose estimation, with the *autocalibration* extension. Welch HiBall at 6.  **Figure 6** Welch HiBall at Fig. 6. **4.3 The Ceiling-HiBall Interface Board** The Ceiling-HiBall Interface Board or CIB (Figure 11) provides communication and synchronization between a host personal computer, the HiBall (Section 4.1), and the Ceiling (Section 4.2). The CIB has four Ceiling ports allowing interleaving of ceiling panels for up to four simultaneous LED flashes and/or higher Ceiling bandwidth. (The Ceiling bandwidth is inherently limited by LED power restrictions as described in Section 4.2, but this can be increased by spatially multiplexing the Ceiling panels.) The CIB has two tether interfaces that can communicate with up to four daisy-chained HiBall units. The full-duplex communication with the HiBall units

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CLAIM 9	HiBall
	uses a modulation scheme (BPSK) allowing future wireless operation. The interface from the CIB to the host PC is the stable IEEE1284C extended parallel port (EPP) standard. The CIB comprises analog drive and receive components as well as digital logic components. The digital components implement store and forward in both directions and synchronize the timing of the LED “on” interval within the HiBall dark-light-dark intervals (Section 5.2). The protocol supports full-duplex flow control. The data are arranged into packets that incorporate error detection. Welch HiBall at 8-9. **4. SYSTEM COMPONENTS** **4.1 The HiBall** The original electro-optical tracker (Figure 3, bottom) used independently housed lateral effect photo-diode units (LEPDs) attached to a light-weight tubular framework. As it turns out, the mechanical framework would flex (distort) during use, contributing to estimation errors. In part to address this problem the HiBall sensor unit was designed as a single rigid hollow ball having dodecahedral symmetry, with lenses in the upper six faces and LEPD on the insides of the opposing six lower faces (Figure 7). This immediately gives six primary “camera” *views* uniformly spaced by 57 degrees. The views efficiently share the same internal air space, and are rigid with respect to each other. In addition, light entering any lens sufficiently off axis can be seen by a neighboring LEPD, giving rise to five secondary views through the top or central lens, and three secondary views through the five other lenses. Overall, this provides 26 fields of view which are used to sense widely separated groups of LEDs in the environment. While the extra views complicate the initialization of the Kalman filter as described in Section 5.5, they turn out to be of great benefit during steady-state tracking by effectively increasing the overall HiBall field of view without sacrificing optical sensor resolution. The lenses are simple plano-convex fixed-focus lenses. Infrared (IR) filtering is provided by fabricating the lenses themselves from RG-780 Schott glass filter material which is opaque to better than 0.001% for all visible wavelengths, and transmissive to better than 99% for IR wavelengths longer than 830 nm. The longwave filtering limit is provided by the DLS-4 LEPD silicon photodetector (UDT Sensors, Inc.) with peak responsivity at 950 nm but essentially blind above 1150 nm. The LEPDs themselves are not imaging devices; rather they detect the centroid of the luminous flux incident on the detector. The x-position of the centroid determines the ratio of two output currents, while the y-position determines the ratio of two other output currents. The total output current of each pair are commensurate, and proportional to the total incident flux. Consequently, focus is not an issue, so the simple fixed-focus lenses work

CLAIM 9	HiBall
	well over a range of LED distances from about half a meter to infinity. The LEPDs and associated electronic components are mounted on a custom rigid-flex printed circuit board (Figure 8). This arrangement makes efficient use of the internal HiBall volume while maintaining isolation between analog and digital circuitry, and increasing reliability by alleviating the need for inter-component mechanical connectors. Figure 9 shows the physical arrangement of the folded electronics in the HiBall. Each LEPD has four transimpedance amplifiers (shown together as one "Amp" in Figure 9), the analog outputs of which are multiplexed with those of the other LEPDs, then sampled, held, and converted by four 16-bit Delta-Sigma analog-to-digital (A/D) converters. Multiple samples are integrated via an accumulator. The digitized LEPD data are organized into packets for communication back to the CIB. The packets also contain information to assist in error-detection. The communication protocol is simple, and while presently implemented by wire, the modulation scheme is amenable to a wireless implementation. The present wired implementation allows multiple HiBall units to be daisy-chained so a single cable can support a user with multiple HiBall units. Welch HiBall at 6-7. **1.3 The HiBall Tracking System** In this article we describe a new and vastly improved version of the 1991 system. We call the new system the *HiBall Tracking System*. Thanks to significant improvements in hardware and software this HiBall system offers unprecedented speed, resolution, accuracy, robustness, and flexibility. The bulky and heavy sensors and backpack of the previous system have been replaced by a small *HiBall* unit (Figure 4, bottom). In addition, the precisely machined LED ceiling panels of the previous system have been replaced by looser-tolerance panels that are relatively inexpensive to make and simple to install (Figure 4, top; Figure 10). Finally, we are using an unusual Kalman-filter-based algorithm that generates very accurate pose estimates at a high rate with low latency, and simultaneously self-calibrates the system. As a result of these improvements the HiBall Tracking System can generate over 2000 pose estimates per second, with less than one millisecond of latency, better than 0.5 millimeters and 0.03 degrees of absolute error and noise, everywhere in a 4.5 by 8.5 meter room (with over two meters of height variation). The area can be expanded by adding more panels, or by using checkerboard configurations which spread panels over a larger area. The weight of the user-worn HiBall is about 300 grams, making it lighter than one optical sensor in the 1991 system. Multiple HiBall units can be daisy chained together for head or hand tracking, pose-aware input devices, or precise 3D point. Welch HiBall at 4.

Exhibit E-11

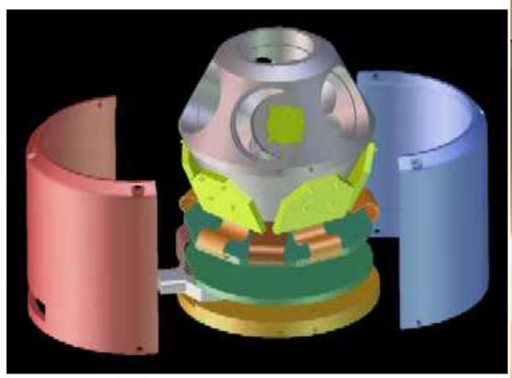
CLAIM 9	HiBall
	The HiBall tracking system resolves linear motion of less than 0.2mm and angular motions under 0.03 degrees without the distortion seen in magnetic trackers. The update rate is greater than 1500 Hz and latency is about 1ms. To our knowledge, this was the first and remains the only demonstrated scalable tracking system for HMDs. UNC HiBall Tracker at 1. **The HiBall** The HiBall is a cluster of 6 lenses and 6 photodiodes arranged so that each photodiodes can view LEDs through several of the 6 lenses, providing 26 view frustra originating at the HiBall. The assembly will include signal processing and A/D conversion circuitry. The total weight is about 5 ounces, making it lighter than just one of the cameras in the previous generation ceiling tracker. The HiBall and the ceiling panel are synchronized by a custom interface board which allows very high rate of LED sightings. The hardware alone can perform more than 3,000 sightings per second, while the whole system tracks using about 1,500. UNC HiBall Tracker at 1. **The Hiball** (Shown without lenses)   UNC HiBall Tracker at 2.

Exhibit E-11

CLAIM 9	HiBall
	The SCAAT algorithm The UNC HiBall Tracker relies on the SCAAT (Single Constraint At A Time) algorithm to compute the user's position and orientation from the individual sightings the HiBall makes of LEDs on the ceiling panels. The algorithm makes innovative use of an Extended Kalman Filter to provide position and orientation updates after each individual LED sighting, rather than after a group of several sightings as in the previous generation of UNC ceiling tracker. In addition, SCAAT improves on previously developed auto calibration techniques to allow on-line calibration as described below. For more information see Greg Welch's SCAAT page which includes links to Greg Welch and Gary Bishop's 1997 SIGGRAPH paper on SCAAT. UNC HiBall Tracker at 2. **Autocalibration** The current ceiling's lower cost design was made possible by an auto calibration process described in Gottschalk93. The SCAAT algorithm improves on this by allowing auto calibration, tuning the actual LED positions, to be performed while the system is tracking. This accommodates shifts in the tiles and LEDs which can occur during normal use. In addition this technique opens possibilities for even less initial knowledge of LED placement than the current ceiling provides. As a test and demonstration of the autocalibration abilities of SCAAT, we have intentionally raised ceiling panels from their correct position. Here Dr. Gary Bishop is shown making the adjustments. The system was given only the initial flat LED positions, but after less than ten minutes of use (successfully tracking with the misplaced panels), SCAAT had accurately adjusted its knowledge of the LED positions through displacements more than 5cm. The above visualization shows the final measured LED positions. UNC HiBall Tracker at 2-3.

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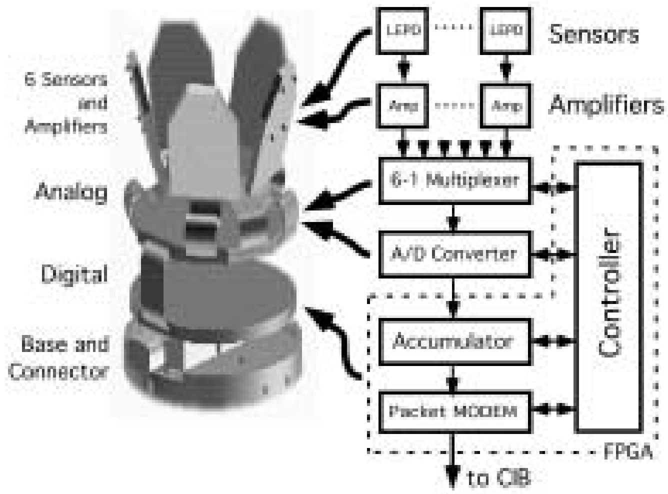
CLAIM 9	HiBall
	 **Figure 9** Welch HiBall at Fig. 9. **4.2 The Ceiling** As presently implemented, the infrared LEDs are packaged in 61 centimeter square *panels*, to fit a standard false ceiling grid (Figure 10, top). Each panel uses five printed circuit boards: a main controller board and four identical transverse-mounted *strips* (bottom). Each strip is populated with eight LEDs for a total of 32 LEDs per panel. We mount the assembly on top of a metal panel such that the LEDs protrude through 32 corresponding holes. The design results in a Ceiling with a rectangular LED pattern with periods of 7.6 and 15.2 centimeters. This spacing is used for the initial estimates of the LED positions in the lab, then during normal operation the SCAAT algorithm continually refines the LED position estimates (Section 5.4). The SCAAT *autocalibration* not only relaxes design and installation constraints, but provides greater precision in the face of initial and ongoing uncertainty in the Ceiling structure. We currently have enough panels to cover an area approximately 5.5 by 8.5 meters with a total of approximately 3,000 LEDs. 1 The panels are daisy-chained to each other, and panel selection encoding is position (rather than device) dependent. Operational commands are presented to the first panel of the daisy chain. At each panel, if the panel select code is zero the controller decodes and executes the operation; else it decrements the panel select code and passes it along to the next panel (controller). Upon decoding, a particular LED is selected and the LED is energized. The LED brightness (power) is selectable for

Exhibit E-11

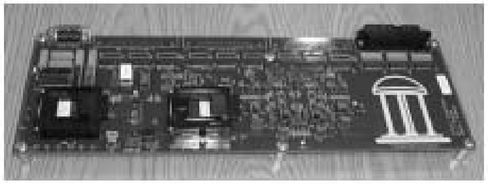
CLAIM 9	HiBall
	automatic gain control as described in Section 5.2. We currently use Siemens SFH-487P GaAs LEDs which provide both a wide angle radiation pattern and high peak power, emitting at a center wavelength of 880 nm in the near IR. These devices can be pulsed up to 2.0 Amps for a maximum duration of 200 with a 1:50 (on:off) duty cycle. While the current Ceiling architecture allows flashing of only one LED at a time, LEDs may be flashed in any sequence. As such no single LED can be flashed too long or too frequently. We include both hardware and software protection to prevent this. **4.3 The Ceiling-HiBall Interface Board** The Ceiling-HiBall Interface Board or CIB (Figure 11) provides communication and synchronization between a host personal computer, the HiBall (Section 4.1), and the Ceiling (Section 4.2). The CIB has four Ceiling ports allowing interleaving of ceiling panels for up to four simultaneous LED flashes and/or higher Ceiling bandwidth. (The Ceiling bandwidth is inherently limited by LED power restrictions as described in Section 4.2, but this can be increased by spatially multiplexing the Ceiling panels.) The CIB has two tether interfaces that can communicate with up to four daisy-chained HiBall units. The full-duplex communication with the HiBall units uses a modulation scheme (BPSK) allowing future wireless operation. The interface from the CIB to the host PC is the stable IEEE1284C extended parallel port (EPP) standard. The CIB comprises analog drive and receive components as well as digital logic components. The digital components implement store and forward in both directions and synchronize the timing of the LED "on" interval within the HiBall dark-light-dark intervals (Section 5.2). The protocol supports full-duplex flow control. The data are arranged into packets that incorporate error detection. Welch HiBall at 8-9.  **Figure 11** Welch HiBall at Fig. 11. **The SCAAT algorithm**

Exhibit E-11

CLAIM 9	HiBall
	The UNC HiBall Tracker relies on the SCAAT (Single Constraint At A Time) algorithm to compute the user's position and orientation from the individual sightings the HiBall makes of LEDs on the ceiling panels. The algorithm makes innovative use of an Extended Kalman Filter to provide position and orientation updates after each individual LED sighting, rather than after a group of several sightings as in the previous generation of UNC ceiling tracker. In addition, SCAAT improves on previously developed auto calibration techniques to allow on-line calibration as described below. For more information see Greg Welch's SCAAT page which includes links to Greg Welch and Gary Bishop's 1997 SIGGRAPH paper on SCAAT. UNC HiBall Tracker at 2. **Autocalibration** The current ceiling's lower cost design was made possible by an auto calibration process described in Gottschalk93. The SCAAT algorithm improves on this by allowing auto calibration, tuning the actual LED positions, to be performed while the system is tracking. This accommodates shifts in the tiles and LEDs which can occur during normal use. In addition this technique opens possibilities for even less initial knowledge of LED placement than the current ceiling provides. As a test and demonstration of the autocalibration abilities of SCAAT, we have intentionally raised ceiling panels from their correct position. Here Dr. Gary Bishop is shown making the adjustments. The system was given only the initial flat LED positions, but after less than ten minutes of use (successfully tracking with the misplaced panels), SCAAT had accurately adjusted its knowledge of the LED positions through displacements more than 5cm. The above visualization shows the final measured LED positions. UNC HiBall Tracker at 2-3. **6.2.2 Complete System Simulations.** To produce realistic data for developing and tuning our algorithms we collected several motion paths *(*sequences of pose estimates) from our first generation electro-optical tracker (Figure 3) at its 70 Hz maximum report rate. These paths were recorded from both naive users visiting our monthly "demo days" and from experienced users in our labs. In the same fashion as we had done for (Azuma & Bishop, 1994a) we filtered the raw path data with a non-causal zero-phase-shift low-pass filter to eliminate energy above 2 Hz. The output of the low-pass filtering was then re-sampled at whatever rate we wanted to run the simulated tracker, usually 1000 Hz. For the purposes of our simulations we considered these resampled paths to be the "truth"—a perfect representation of a user's motion. Tracking error was determined by comparing the "true" path to the estimated path produced by the tracker. The simulator reads camera models describing the 26 views, the sensor noise parameters, the LED positions and their expected error, and the motion path described above. Before beginning the simulation, the

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CLAIM 9	HiBall
	LED positions are perturbed from their ideal positions by adding normally distributed error to each axis. Then, for each simulated cycle of operation, the "true" pose are updated using the input motion path. Next, a view is chosen and a visible LED within that view is selected, and the image-plane coordinates of the LED on the chosen sensor are computed using the camera model for the view and the LED as described in Section 5.3. These sensor coordinates are then perturbed based on the sensor noise model (Section 6.2.1) using the distance and angle to the LED. Now these noise corrupted sensor readings are fed to the SCAAT filter to produce an updated position estimate. The position estimate is compared to the true position to produce a scalar error metric described next. Welch HiBall at 16-17. **5.4 On-line LED Autocalibration** Along with the benefit of simplicity and speed, the SCAAT approach offers the additional capability of being able to estimate the 3D positions of the LEDs in the world concurrently with the pose of the HiBall, on line, in real time. This capability is a tremendous benefit in terms of the accuracy and noise characteristics of the estimates. Accurate LED position estimates are so important that prior to the introduction of the SCAAT approach a specialized off-line approach was developed to address the problem (Gottschalk & Hughes, 1993). The method we now use for autocalibration involves defining a distinct SCAAT Kalman filter for each LED. Specifically, for each LED we maintain a state $\bar{l}$ (estimate of the 3D position) and a 3x3 Kalman filter covariance. At the beginning of each estimation cycle we form an augmented state vector $\hat{x}$ using the appropriate LED state and the current HiBall state: $\hat{x} = [\bar{x}^{\mathrm{T}}, \bar{l}^{\mathrm{T}}]^{\mathrm{T}}$. Similarly we augment the Kalman filter error covariance matrix with that of the LED filter. We then follow the normal steps outlined in Section 5.3, with the result being that the LED portion of the filter state and covariance is updated in accordance with the measurement residual. At the end of the cycle we extract the LED portions of the state and covariance from the augmented filter, and save them externally. The effect is that as the system is being used, it continually refines its estimates of the LED positions, thereby continually improving its estimates of the HiBall pose. Again, for additional information see (Welch, 1996; Welch & Bishop, 1997). Welch HiBall at 13. The Kalman filter requires both a model of the process dynamics, and a model of the relationship between the process state and the available measurements. In part due to the simplicity of the SCAAT approach we are able to use a simple PV (position-velocity) process model (Brown & Hwang, 1992). Consider the simple example state vector $\bar{x}(t) = [x_p(t), x_v(t)]^{\mathrm{T}}$ where the first element $x_p(t)$ is the pose (position or orientation) and the second

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	element $x_v(t)$ is the corresponding velocity, i.e. $x_v(t) = \frac{d}{dt}x_p(t)$. We model the continuous change in the HiBall state with the simple differential equation $$\frac{d}{dt}\bar{x}(t) = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} x_p(t) \\ x_v(t) \end{bmatrix} + \begin{bmatrix} 0 \\ \mu \end{bmatrix}u(t), \quad (1)$$ where *u(t)* is a normally-distributed white (in the frequency spectrum) scalar noise process, and the scalar μ represents the magnitude or *spectral density* of the noise. We use a similar model with a distinct noise process for each of the six pose elements. We determine the individual noise magnitudes using an off-line simulation of the system and a non-linear optimization strategy that seeks to minimize the variance between the estimated pose and a known motion path. (See Section 6.2.2.) The differential equation (1) represents a continuous integrated random walk, or an integrated *Wiener* or *Brownian-motion* process. Specifically, we model each component of the linear and angular HiBall velocities as a random walk, and then use these (assuming constant inter-measurement velocity) to estimate the HiBall pose at time *t* + *δt* as follows: $$\bar{x}(t+\delta t) = \begin{bmatrix} 1 & \delta t \\ 0 & 1 \end{bmatrix}\bar{x}(t) \quad (2)$$ for each of the six pose elements. In addition to a relatively simple process model, the HiBall measurement model is relatively simple. For any Ceiling LED (Section 4.2) and HiBall view (Section 4.1), the 2D sensor measurement can be modeled as $$\begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} c_x/c_z \\ c_y/c_z \end{bmatrix} \quad (3)$$ where $$\begin{bmatrix} c_x \\ c_y \\ c_z \end{bmatrix} = VR^{T}(\hat{l}_{xyz} - \bar{x}_{xyz}), \quad (4)$$ is the camera viewing matrix from Section 5.1, is the position of the LED in the world, is the position of the HiBall in the world, and is a rotation matrix corresponding to the orientation of the HiBall in the world. In practice we maintain the orientation of the HiBall as a combination of a global (external to the state) quaternion and a set of incremental angles as described in (Welch, 1996; Welch & Bishop, 1997).

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	Welch HiBall at 11-12. **5.2 On-Line HiBall Measurements** Upon receiving a command from the CIB (Section 4.3), which is synchronized with a CIB command to the ceiling, the HiBall selects the specified LEPD and performs three measurements, one before the LED flashes, one during the LED flash, and one after the LED flash. Known as “dark-light-dark”, this technique is used to subtract out DC bias, low frequency noise, and background light from the LED signal. We then convert the measured sensor coordinates to “ideal” coordinates using the calibration tables described in Section 5.1. In addition, during run time we attempt to maximize the signal-to-noise ratio of the measurement with an automatic gain control scheme. For each LED we store a target signal strength factor. We compute the LED current and number of integrations (of successive accumulated A/D samples) by dividing this strength factor by the square of the distance to the LED, estimated from the current position estimate. After a reading we look at the strength of the actual measurement. If it is larger than expected we reduce the gain, if it is less than expected we increase the gain. The increase and decrease are implemented as on-line averages with scaling such that the gain factor decreases rapidly (to avoid overflow) and increases slowly. Finally we use the measured signal strength to estimate the noise on the signal using (Chi, 1995), and then use this as the measurement noise estimate for the Kalman filter (Section 5.3). Welch HiBall at 9-10. *See also* /hiball/src/libs/tracker and /cib, including but not limited to the following: /hiball/src/libs/tracker/ceiling.h /hiball/src/libs/tracker/tracker.cpp /hiball/src/libs/tracker/tracker.h *See also* Defendants’ Invalidity Contentions for further discussion.